S. G. LUNDGREEN

ECONOMICS AND OPERATION OF ALTERNATING-CURRENT AND DIRECT-CURRENT SYSTEMS: A COMPARATIVE STUDY

GRADUATE THESIS

BOSTON UNIVERSITY

COLLEGE OF BUSINESS ADMINISTRATION

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SYNOPSIS

This thesis deals with an important problem of engineering economics; namely, an economic comparison between alternating-current and direct-current systems. Of necessity, certain of the simpler technical aspects of the problem have been considered, since the optimum solution of any particular problem must strike a balance between economic benefits and operating facilities.

The introduction treats of the subject in a general way, points out the aims of the thesis, and considers its relation to a study of business administration.

The first chapter presents the application of the two systems to various services and illustrates this by considering four widely different industries.

The second chapter explains some features of the generation and the distribution of electric energy and emphasizes in particular the cost of electrical service.

The third chapter deals with transmission problems, and the direct-current system is given particular attention.

The fourth chapter is a general survey of electric railway practice in various countries and attempts to explain the wide diversity of opinion regarding the relative merits of the two systems.

The bibliography enumerates all books, articles, and reports which have been consulted in the preparation of the thesis.

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APPLICATION OF ALTERNATING-CURRENT AND DIRECT-CURRENT

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INTRODUCTION

SUBJECT MATTER

General. Engineering economics may be defined as that field of knowledge which is concerned with the economic results of engineering, and the application of the principles and laws of economics to engineering enterprises.

"Engineering undertakings are with very few exceptions suggested by economic desires and are governed by economic requirements. Therefore, the application of science to every part of an engineering structure should always be based on economic grounds; that is, the principles of design are subordinate to the principles which underlie economic judgment."[a] The engineer's ultimate aim is to accomplish a desired result at a minimum cost. The desired result depends upon the type of service wanted. In some fields service is of paramount importance, because the economic success of the system depends upon reliability and continuity of service. In such a case service comes first and economy in design and construction comes second, but it is still seen that ultimate economy is the basic principle.

Elements of Engineering Economics.[b] To illustrate the multiplicity of problems arising in the economics of engineering enterprises the following classification may be suggestive:

A. Cost analysis.

1. Principles of accountancy
2. Capital and operating charges
3. Total annual charges
4. Cost per unit
5. Fixed and variable costs
6. Cost balance

a) 1-p.3 b) 81-p.1983

B. Social - Economic investigations.

I. Statistics of Consumption

2. Traffic analysis

3. Probable future developments

C. Valuation of Property.

I. Purchase or sale

2. Taxation

3. Issuance of securities

4. Adjustment of book values

D. Rate Making.

I. Public uutilities

2. Common carriers

E. Social - Political Relations

I. Public relationship

2. Regulation

3. Legislation

4. International relations

Scope of Study The present study deals with one problem arising in electrical engineering, namely the relative merits of alternating-current and direct-current systems considered from an economic and technical viewpoint. The main thought of the thesis is therefore a comparison of the two systems pertaining to operation, capital, operating charges and total annual charges. However, other problems of interest in the economics of electric service are considered so that all five groups of the elements of engineering economics are at least mentioned.

The different phases of electric service have been treated as comprehensively as possible within the limited space of a thesis. An investigation is made of the application of alternating-current and direct-current systems to generation, transformation, transmission, con-

version and distribution as well as the use of electric power in industrial and domestic applications and for railway service.

Appropriateness of subject matter. Since nowadays the electrical industry in all its ramifications, such as manufacture, generation, distribution, transportation etc., is perhaps the most important of all industries, and business enterprises it is singularly appropriate that such a study should be undertaken in connection with a study of business administration. The electrical industries, public utilities and common carriers call for the highest degree of executive ability both in technical and economic matters. They require experts in both fields. They call for the best legal and political services in connection with legislation and regulation and they intimately enter into the daily life of every person living in a modern community.

The reason why the subject has been somewhat neglected until recently is probably that an intelligent treatment of the subject must necessarily be undertaken by engineers and they are generally more interested in the development of apparatus and systems and the refinement of design than in general economics. This has been the natural consequence of the ever-pressing technical problems confronting engineers and also of the specialization required in such work.

The appropriateness of content and form will be dealt with later.

Type of study and method of approach The present study is a library study which requires original investigation in a particular field of the literature available on the subject, the reviewing and critical evaluation of such material and the drawing of conclusions and deductions.

The method to be followed in the preparation of a library study falls naturally in the following steps: Selection of subject, collection and arrangement of material and the writing of the thesis.

I. <u>Selection of subject</u> It is required that the subject shall be in some special field of business. In general the student will naturally select a field in which he is particualarly interested or in which he has special knowledge. This in the first place makes it a pleasure for him to do the work. In the second place, it enables him to select and criticize his material and it increases his special knowledge, inducing him to further study in the field. In the third place, it may be that his increased knowledge and special study will be of value to him in his business connection and will call his employer's attention to his interest in the field and possibly to his ability to deal with and present material of interest to the employer.

In this particular case the writer has always been interested in the subject of economics. His training in engineering made it natural for him to select the field of engineering economics and as he had been doing some work in connection with the economics of alternating-current and direct-current systems applied to a spedial field, the subject matter more or less presented itself to him.

The writer could have limited himself to the special field mentioned but as the material available for his use was insufficient because of the requirements as to length of thesis, the field had to be broadened and instead of writing on a few phases of electrical engineering the writer chose to write in a very general way on the economics of practically all phases where the question of alternating-current versus direct-current may appear.

2. <u>Collection of material</u> The next step is the collection of material. Of course, some source of information must be available to the student, from which he must be able to find such material as is applicable to his thesis and he must be able to understand it and review it intelligently and take such notes as may be of use to him.

The source of information available to the writer is referred to at another place. At first a general search was made in library indexes for material covering the whole subject and the articles found were read and reviewed in the form of notes or quotations. At this step the writer acquainted himself with the literature of the specific subjects and learned to select the most useful publications for the different parts of his thesis. Later, when each phase of the subject was studied by itself the latter publications were searched and additional material was collected.

3. Arrangement of material This step should first be taken when a subject has been studied as far as the student wishes to go. He should then arrange his material in an orderly and logical manner and exclude irrelevant matters. He should try to find connecting points so that the subject will be presented in a coherent manner.

This phase was undertaken by the writer for one chapter after another when they had been studied sufficiently.

4. Writing of thesis After the procedure outlined above has been accomplished the final presentation of the material can be done without much difficulty.

Similarly to the above, each chapter has been written in the final form when studied sufficiently and only a few additional sections have later been inserted.

Limits of study Being a library study it limits itself to reference work already done and published and no attempt has been made to try an individual and independent treatment of the subjects as this would require considerably more information than is given in the papers referred to. Furthermore, each particular problem might require extensive investigation over a great length of time and necessitate the use of coworkers.

CONTENT

Resume of the field. Electrical energy to-day is available for use in two forms that differ materially from each other. One is the direct-current form, the other the alternating-current form.

Electrical energy can be generated, transmitted, distributed and used in either form and both forms have technically inherent advantages and disadvantages for the different uses of electric service. The relative merits of these advantages and disadvantages govern the system which shall be used for any specific purpose and the present study aims to point out these relative merits and to explain why the applications of the systems have changed from time to time and why there is at present such a variance in the practice of different countries and communities even for the same field of electric service. A few historical notes may be of interest in this connection. In the early days of commercial utilization of electrical energy, the electricity was generated by small direct-current machines and distributed in the immediate vicinity of the generating station.

In Europe a transmission system was developed using high-tension direct-current, but three-phase alternating-current was generally used for distribution. In America Edison developed the three-wire direct-current system used extensively for distribution, but in recent years a very rapid development of the alternating-current networks has caused the alternating-current distribution to take a lead over the direct-current system so that now only few metropolitan areas are served by direct-current and it is only a question of time when this will disappear, since large utilities having direct-current distribution contemplate a gradual change to alternating-current.

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former and is more flexible for combined transmission and high-tension distribution. This latter system has very materially aided in the general adoption of electricity for all power and light purposes.

In America the direct-current transmission system was never introduced but the alternating-current system has had an enormous development and will most likely prevail in the future.

However, as more remote water-power sites are developed, which require extra long straight transmission it is possible that high-tension direct-current may be used for such transmission as this system has important technical advantages for this type of transmission.

Therefore, in different parts of the world large projects of transmission by direct-current are being studied because by this system there seems to be a possibility of a material increase in amount of power transmitted without affecting the safety and reliability of operation. The crucial point of this scheme is the generation and transformation of high-tension direct-current, but as the most recent years have seen important developments of machinery for such purposes those technical difficulties may be overcome.

Electrical operation of traction system was first used for street cars and direct-current was and is still used almost universally. Accumulator locomotives have been tried in Italy for traction over longer distances, but are now used for traction only in some industrial applications.

In Europe there was developed the single-phase traction system which was adopted by many countries because of the high tensions which can be used on the catenary, but other countries adopted the direct-current system. In America both systems are used extensively, but it seems as if the application of high-tension mercury-arc power rectifiers may give an impetus to the direct-current traction system. However, in no other field of electric service is there such a confusion of systems and such a controversy of opinion as in the electric traction field.

For industrial applications the direct-current system served its purpose very well as long as the plants were comparatively small. Barely a decade ago the concensus of expert opinion in Europe was largely in favor of the generation and transmission of direct-current, more especially in view of the requirements of the drives for rolling mills in steel works or hoisting machinery in all industries. In America the progress went in the opposite direction, a condition of affairs sufficiently indicative of the suspicion that the ideal resided as usually in the mean. Now, the two systems are often operated side by side, the use of either system depending upon the character of the service, but alternating-current can at present be used for almost all types of service.

Source of information

It has been of great value to the writer in preparing the thesis that he was able to consult the technical literature of many different countries. He has corresponded with friends in this country and abroad and obtained

(continued next page)

valuable reports which are otherwise not easily obtained and the content of which is not accessible to most Americans. One valuable report is the one on railway service published by the Norwegian Institute of Engineers (Reference #115). Another is the report on inter-Scandinavian transmission published by a joint Danish-Swedish-Norwegian Commission (Reference # 100)

The main source of information however, is the United Engineering Societies Library in New York City, where a great deal of the technical literature of the world is available for reference. To begin with the general index was searched for text books and other material. Very little was found in this way, but a few leads to special bibliographies in various books were obtained. Books are, as a rule, of comparatively little use for obtaining information on special or recent topics in electrical theory or practice. An exception is a book by Reyneau and Seelye "Economics of Electrical Distribution" (Reference #38); another with a wealth of cost material and references is H.P. Gillette "Cost Handbook of Mechanical and Electrical Engineering" (Reference #12). For new books one should consult book reviews in periodicals.

"By far the most useful single help in a search for information on electrical subjects is "Science Abstracts, Section B, Electrical Engineering." This publication gives brief abstracts of the most important original articles and papers which appear in electrical periodicals throughout the civilized world." a) "The Engineering Index" and "Industrial Art Index" contain titles of important electrical articles. "International Catalogue of Scientific Literature" goes up to 1914. Some of the articles referred to have valuable special bibliographies. Other sources of complete bibliographies on special subjects are "National Electric Light Association, Proceedings", and "General Electric Review."

a) 11-p.1380

National Electrical periodicals are:[a]

I. American Institute of Electrical Engineers, monthly Journal, annual Transactions.
2. National Electric Light Association, monthly Bulletin, annual Proceedings.
3. Institution of Electrical Engineers, London, monthly Journal,
4. Association Francaise des Électriciens, Paris, monthly Bulletin.
5. Elektrotechnische Zeitschrift, Berlin, a weekly.
6. Elettrotecnica, Rome, three times a month.

Other Electrical periodicals

7. Electrical World, New York.
8. The Electrician, London.
9. Electrical Review, London.
IO. La Revue Génerale de l'Électricité, Paris.
II. Elektrotechnik und Maschinenbau, Vienna.

Manufacturers' publications Many valuable articles may be found in such periodicals, although some of the information issued has to be taken with a grain of salt. The best known are:

I2. General Electric Review, Schenectady, New York
I3. Electric Journal (Westinghouse) Pittsburgh, Pa.
I4. Beama (British Manufacturers) London
I5. A.E.G. Mitteilungen, Berlin
I6. Siemens Zeitschrift, Berlin
I7. B.B.C. Mitteilungen (Brown Boveri) Switzerland

Those periodicals mentioned do not by any means give a complete list of electrical periodicals, but they are the most important ones.

For the purpose of the present study the first three were found extremely valuable, although #I is rather technical. Also #4,5,7,8, and 9 contain important data on economics. On special problems #I2, I3 and I7 give valuable information.

Amount of work done A perusal of the earlier technical literature will reveal any amount of technical matters, but very little economics.

a) II- p.1381

However, lately this latter phase of engineering is attracting considerable attention and one finds regularly in certain types of periodicals subjects dealing with the economics of all phases of engineering. The use of accurate annual costs as a basis for determining the most economical installation goes back to Lord Kelvin. Since then a great deal has been written on the subject and much valuable information can be found in the technical literature. But much material has not been published, particularly reports submitted by consulting engineers to public utilities or railroad companies, because these reports cover the present and future economics of those companies and the information in them is held strictly confidential, since it may affect the rate making and regulation from special commissions.

Such reports as that on the adoption of a new system for distribution cover the subject in the most thoroughgoing way and embrace both the technical and economic problems of the particular system. The method followed was to study the history of the particular utility for a number of years back by means of statistics and on the basis of that study to predict the future for perhaps the next ten years and to make suggestions as to future extensions and the possible adoption of a new system. This new system must at least be comparable in reliability to the old system and therefore an extensive fault analysis is made based on the records in order to find the past reliability of service. To find the probable future load a careful load growth study is made for the following ten years; to find the elements of cost of service in the past a detailed allocation of cost to all the different phases of service is undertaken; to find the future investment and cost of service an actual lay-out of the future system is made and an estimate of cost is prepared, assuming that a new system is substituted and either all new loads or only a certain part of the new load is taken by the new system, the

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rest being taken by the old system operating alongside the new system.

In the first case a complete change-over of the present loads to the new system may also be considered, but is usually found to involve prohibitive costs, so that the method suggested in some cases is to have the old and the new system operating together in the same district but preventing the old and uneconomical system to grow by encouraging new loads to be taken by the new system and perhaps letting the old system decrease as old buildings are torn down and new ones erected, whose loads are taken by the new system. In other cases it may be suggested to restrict the old system to a certain district and let all new areas be served by the new system.

Such reports are of the greatest value to the particular utility, but the results found are not generally applicable to other conditions.

A great deal of investigation covering another field has been made in the preparation of reports submitted to various governments or railroad companies concerning the electrification of railways. Such reports make a general survey of the practise in different countries and investigate the records and the desirability of adopting any one of the systems for particular installations. While it is not possible to generalize from those reports, because they often come to opposite conclusions, they still give much valuable information and may serve as a guide for similar investigations.

When national policies are concerned, for example the unification or consolidation of electric utilities or a particular interstate or international transmission project, ~~is considered~~ the various governments involved may appoint special commissions to make exhaustive investigations of the problems.

The reports from such commissions are sometimes published and furnish much valuable and interesting information.

Critical evaluation of work done

The reports mentioned above are collected and written by the most eminent experts in the field on the basis of many years' study and experi-

ence and usually the material presented is such that only a similar and parallel investigation involving very considerable work and cost could be compared to it. These reports are in the highest degree analytical of the special problem and both as to technics and economics they rank very high. To attempt a critical evaluation of such work would be impertinent and also impossible for the writer since it would require vastly more experience and knowledge and a much greater availability of suitable material than the writer has.

As to other material referred to it may be said that some of it is of the highest substance, while some of it contains very little meat. The writer is conscious of his limitations and does not consider it within his competence to criticize to any great extent the works and articles referred to. But care has been taken to refer to such works as have appeared in recognized periodicals and have been written by acknowledged experts and authorities. Even in such cases where the cost data may seem low, the writer has abstained from making comments because he is in no position to check up on prices in different countries at different times. Moreover, no cost data are quoted for the purpose of being used analytically or for specific problems, but merely for the purpose of illustrating methods and principles involved in the solution of such problems.

That a critical evaluation of such material is a matter which requires unusual knowledge and experience is evidenced by the fact that so very few critical reviews appear in the current literature. Only very occasionally can they be found, but the writer has, whenever they have come to his knowledge, referred to them. On the other hand, these critical reviews emphasize how difficult it is to write on economics in general terms.

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Need for the present study, its significance and aims To the best of the writer's knowledge there is no comprehensive general treatment of the subject although it is of the greatest importance. There is no doubt that it is difficult to write an exhaustive treatise on all phases of engineering economics and quite particularly on such a special problem as the present one. The difficulty is first the compiling and collecting of statistics, especially authoritative and reliable statistics, relating to engineering enterprises, because the material is usually not published and because it varies so much.

Another difficulty is that such a study of economics must of necessity be made by engineers and they are too much tempted to delve into mathematical methods of approach. This was the case with most articles found in the current literature and when the authors attempted to write in general terms on certain problems it was very noticeable how little of value there was in the articles.

The present problem has not received in the current literature the attention which its importance would warrant. Often one finds a phrase like this: "This subject has caused considerable discussion" and then a few passing remarks are made on the subject but no reference is given where such a discussion may be found. The writer has corresponded with several library search experts, but they could give very little help, writing for example: "There does not appear to be very much on the subject that is satisfactory... If eventually you do find a satisfactory source of information, I shall be very glad to know what it is." Yet, the significance of a comparative study of the economics and operation of alternating-current and direct-current systems has in recent years become more and more apparent, as is evidenced by the great amount of money certain utilities spend on such studies.

The present study therefore aims to point out the relative merits of the different systems and also to collect a source of information for

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further study of the field. To this end an intensive library search was undertaken and a rather comprehensive bibiliography collected.

Appropriateness of content The close relationship between technical and economic problems has already been pointed out. They cannot in fact be treated separately in practice, because in engineering the technical and economic aspects of a problem go side by side and play an equally important rôle for the success of the undertaking. But where there is a choice of more than one possible design which is satisfactory from an electrical standpoint, the decision should be based on a study of the relative economics of all the alternatives considered. No argument should be required as to the advisability or rather necessity for the application of economic principles to engineering design. Engineering should make for efficiency but there can be no real efficiency unless there also is accomplished economy.

In the early days of electrical application the systems were laid out more or less by rule of thumb methods because of insufficient knowledge of the technical problems. Economical design was not even considered since it had not yet been brought to the attention of the engineers. Nowadays economics play a predominant rôle in engineering design and it may be said that economical design is the governing factor for all engineering enterprises.

In the present paper special emphasis has been laid upon the economic aspects of the problems, but no comparison would be complete that did not take into consideration the technical sides of the problems and therefore the methods of operation are reviewed in some detail.

The objection may be raised that the review of the technical problems takes up a greater space than the economic considerations. But it will almost invariably be found that even when the discussion is about apparently purely technical matters, an economic consequence always lies behind it and in the review of methods of operation the underlying thought is

some economic consideration.

For example, the term efficiency may sound very technical for a casual reader or it may have lost its real significance for him because the term has been overused in all sorts of connections. But an engineer usually thinks of economy when he speaks of efficiency.

As regards the content in relation to the title it should be brought out that the main thought of this thesis is the economics of electrical systems and "A Comparative Study" applies only to those phases where a comparison between different systems may be made. An effort has been made to emphasize specifically a direct comparison between alternating-current and direct-current systems as such, but as several schemes of each system are practicable and in actual operation, a comparison of different alternating-current and different direct-current systems must be included to give a complete picture. Likewise a few other phases of comparative studies have been included.

Not a technical paper That this is by no means a technical paper should be borne in mind particularly by a technically trained person who may find that the technical points have been treated superficially and perfunctorily, because important technical matters, which in practice may have the greatest influence upon the economics of the plant, have sometimes been only touched upon and mentioned more or less in passing.

Most of the problems discussed are very elementary, but the application of them is often of fundamental importance for the economical operation of the system.

Only occasionally has the most elementary mathematical apparatus been introduced to bring out a special point; otherwise the mathematical calculations are omitted in the thesis and only the results are listed in

tabular or graphical form. Very few electrical formulas and connection diagrams are included as these were felt to be outside the scope of the thesis, and when a diagram is included it is because a diagram in such cases is the best and easiest way of explaining a certain thing in a small space.

Findings and results For each problem investigated there is a statement of findings applied to this particular case. In some cases there are decided advantages in favor of the alternating-current system, in others the opposite holds true. The main result of the study is that both systems have served and still serve their particular fields, and even inside of these fields there is an overlapping in the application of the systems. Some countries, because of adopted practice, are in favor of different alternating-current systems whereas others prefer the direct-current system.

Conclusions and deductions No definite conclusions are arrived at as the broad question of giving preference to any one system can but be determined by a detailed investigation of any given case covering both engineering and economic features.

In general it may be said that the alternating-current system is at the present time the preferred system, but it must be concluded that direct current is an indispensable supplement to alternating-current, because it can redress some of the inconveniences of alternating-current in regard to inflexibility in the operation of motors for industrial application.

In transmission problems the opposite may be said, namely; that the alternating-current system is the predominant one because of its flexibility in operation as regards ease of raising and lowering the pressures and of combining a long-distance transmission system with a high-voltage distribution system.

For distribution there is a strong tendency towards abandoning the direct-current system and substituting in its stead a low-voltage alternating-current distribution network. It is possible that within thirty years the old Edison system of distribution will have entirely disappeared unless some unforeseen developments take place.

For railway service there is the greatest variance of systems. Both the alternating-current and the direct-current systems are used in many forms and they all seem to give satisfactory service.

As to future possibilities and developments a few words may be said. One problem to be solved is the storage of electricity. A means for storing alternating-current has not yet been found whereas for storing direct-current in moderate quantities the accumulator is a very simple and efficient medium. If this could be developed for large amount of power at low cost it is possible that this might give an impetus to a come-back of direct-current applications where alternating-current has superseded the direct-current.

The rapid development of the mercury-arc rectifier has given an impetus to the application of direct-current for railway service and this will probably be more marked in the future, when the rectifier will be developed to use still higher voltages, because the direct-current motor is undoubtedly the superior motor for traction service.

Large amounts of power are now being transmitted over long distances, but future requirements demand a further development. To serve the future needs of metropolitan areas it may be required to deliver concentrated loads of a million horsepower to such areas and a large amount of this may be supplied by remote hydro-electric stations.

The use of high-tension direct-current for extra-long distance transmission seems to offer great possibilities in the future, but the question is: Will higher voltages for alternating-current, lower frequencies, or direct-current be used for transmitting large blocks of power over long distances?

FORM

Each phase of the subject and each problem have been treated separately with an introduction, a main body and conclusions.

The numbers in the footnotes are used to indicate the source of information by reference to the numbered sources in the bibliography. Occasionally, when reviewing the reports of special commissions, no reference to page is given as a general digest of the complete report is presented.

In referring to foreign articles no attempt has been made to subsitute American money for European money, as this could be very misleading because the price level is so different in the various countries. Likewise the metric system has been retained when this was used in the references.

Appropriateness of form. The thesis should be written in such a form that a casual reader can understand it. Of course, it may be possible to write any thesis in such a general way and in such general terms that any layman can understand it, but it is a real difficulty to convey special information on any subject without using the vocabulary and terminology of the particular field.

Therefore, in the present paper, an understanding of the engineering features of electrical enterprises is assumed, but an endeavor has been made to write it in as fluent and ordinary a language as is consistent with the problem and not to use an excess of technical terms and expressions.

THE VALUE OF THE STUDY

The value of writing a thesis has a twofold significance. First, there is the value of the study to others and second, the value to the student.

As regards the value to others the writer considers the collection of the bibliography of great importance. It may give a valuable help in pursuing a further study of a special field. It provides a reference to some of the material available, but scattered throughout the current literature and obtainable only by an extensive special search. The thesis gives a survey of what has been done in the special field and by calling attention to a great number of outstanding accomplishments it may give a broader outlook and a better understanding of the features and problems of one of the world's greatest industries. The thesis also refers to some special reports which are probably not known in this country and not accessible to most Americans, thereby explaining some peculiar conditions in foreign countries, which may be of interest in this country.

The data on cost should be treated with great caution. They are not included to be used on any other specific project but only serve the purpose of illustrating a special problem and of explaining why a certain conclusion has been arrived at for this problem.

Costs of material and labor and methods of construction and operation vary considerably from one locality to another and for different periods of time. Any estimate of a general character is at best more or less misleading when applied to a specific problem. However, the data referred to may be taken as examples of methods to be followed in similar investigations. The basic idea of all economical design is that the total annual charges should be a minimum consistent with good service.

The value of the study for the student is manifold. In the first place it will pay a young engineer to become familiar with methods of obtaining published information on an electrical topic in a systematic way and to be fluent in its use early in his professional career. Then when a rush problem comes he will be able to obtain the desired information within a comparatively short time and with the assurance that no important source has been overlooked. To use a library intelligently is not at all a simple and easy task without expert guidance. Library catalogues are often unsatisfactorily cross-indexed and very often books are insufficiently indexed.

Next the student may learn to present his material in an orderly and logical consequence and to perfect himself in the proficient use of the English language. He may get valuable knowledge and be induced to further study of the field, etc.

The best assurance for the student that he has derived some real benefit from preparing and writing his thesis is that he can say at the end of his study: "If I should start it all over again how much better could I not have done it?"

CHAPTER 1

APPLICATION OF ALTERNATING-CURRENT AND DIRECT-CURRENT

APPLICATION OF ALTERNATING-CURRENT AND DIRECT-CURRENT

General For certain purposes alternating-current and direct-current can be used equally well. In particular is this true where the heating effect of the current is desired, such as cooking and heating, lighting of carbon and incandescent lamps; in the last case a reservation must be made regarding the frequency of the alternating-current, because below a certain frequency an annoying flickering of the light can be noticed.

Direct-current is essential for such purposes where chemical changes are desired, for example, in charging storage batteries or for electroplating purposes. For other purposes it is better such as operating arc lamps because the efficiency of the arc is lower in the alternating-current type[a]; both electrodes are raised to a high temperature, but neither attains the high temperature of the anode in the direct-current arc. Direct-current is also better for tantalum incandescent lamps which antedated the tungsten lamp. Alternating-current effects a serious crystallization of the tantalum filament so the use of this type of lamp was practically restricted to direct-current systems. Used upon alternating-current of 60 cycles its life was only about one quarter of that upon direct-current.[b]

Regarding the operation of the tungsten filament lamp some differences on the two systems can be noticed. On a 60 cycle alternating-current supply there is a slightly higher mortality rate coupled with a slightly better candle-power maintenance than is experienced when the lamps are operated upon direct-current. The one effect just counterbalances the other so that the useful life is not greatly different on direct-current and on alternating-current systems.[c]

a) 81-p.1150 b) 81-p.1135 c) 81-p.1141

It is particularly in the application of electric motive power that the direct-current for certain types of drive~~s~~ gives marked advantages, because the direct-current-motor has a very flexible operation, both in regard~~s~~ to adjustable speed in industrial applications and to variable speed dependent upon the load for example in elevators and cranes and also where quick acceleration is desired, as in electric traction. Where uniform unvarying speed is desired the alternating-current induction motor gives the best results.

The direct-current system has been used a great deal for distribution principally because of the direct availability of the storage battery as a reserve and a load regulator. Perhaps there has been a feeling of greater safety with direct-current for lighting purposes, since the wires are in no way associated with high voltage conductors. An important advantage for direct-current distribution has in the past been its freedom from power-factor, reactance and skin effect, which results in superior voltage regulation in heavily loaded low voltage circuits. For those reasons has the direct-current been in general use for distribution in congested city districts.and the Edison-three wire system has been largely used. In recent years some important direct -current systems have been changed or proposed to be changed because of the development of the alternating-current distribution networks.

Direct-current is generally used in small isolated plants where a large number of minor auxiliary drives are used. In such a case where the generating unit can be located very close to the load it can be operated at the voltage used on the distribution system. But for larger motors it would be practically impossible to transmit and distribute direct-current, as 500 volts is the safe limit that can be used in connection with many of the auxiliary drives.

Direct-current generators are usually compound wound and have

desirable features, such as self-excitation and self-regulation, but as a rule the direct generation of a large amount of direct-current power is not economically desirable. To generate it efficiently large units must be used in a central plant. When this is done in a large manufacturing plant the distribution of the output at 250 volts is not a satisfactory solution and to decentralize the generation is still more costly. Therefore, a heavy direct-current can in general be more economically secured by the conversion of alternating-current, and in case the direct-current load is more than a mile distant from the generating station this method becomes an economic necessity.

"The advantages of alternating-current are chiefly those incidental to its flexibility of voltage transformation and control, which makes possible an extended range of economical transmission and the independent regulation of separate feeders and lines."[a)]

Polyphase alternating-current generators are less expensive than direct-current machines. They have good voltage regulation and are adaptable to much higher speed being free from commutator limitations. Small low-speed alternators are usually provided with individual exciters, often on the same shaft, but large alternators are supplied with exciting current from a central system comprising several exciters in parallel.

The voltage generated for alternating-current systems is usually the same as that used for primary distribution when the latter is below I5 000 volts. In most systems of small and medium capacity the alternating-current line voltage is 2300. The secondary distribution system is supplied by transformers which lower the voltage to the one desired for lighting or auxiliary power. In America the range of voltage is from I00-I25 volts, in Europe 200-250 volts have been used to a great extent. The higher voltages make it possible to distribute

a)16 - p. 924

power more economically, the lower voltages are better adapted for the construction of incandescent and arc lamps.

The standard lighting frequency in America is 60 cycles although in certain parts of California it is 50 cycles. The latter frequency is standard in Europe. For incandescent lighting, 35 cycles[a] appears to be the approximate lower frequency limit for satisfactory service of all classes, although for many purposes 25 cycles lighting has been found satisfactory. This has for example been used in certain parts of Sweden. However, the flicker phenomena are so complicated by a number of physical and physiological factors, that no unqualified definite statement can be made as to the lowest frequency upon which lamps may be operated without causing undue annoyance.[b]

A frequency of 25 cycles has many advantages for overhead transmission and for conversion to direct-current by synchronous converters. Power transmitted at 25 cycles is frequently converted to 60 cycles for lighting purposes by the use of frequency changing motor-generator sets. In Italy where three-phase traction motors are used for the electric railways a frequency of 42-1/2 or 45 is used and in a few cases where a large load of induction motors is associated with a lighting system the compromise frequency of 40 cycles is employed.

Phases Single-phase is used extensively for railway electrification because of the high voltages applicable to a simple catenary construction and also because of the favorable operating features of the single-phase traction motor.

The three-phase system has been used to a limited extent on some Italian Railways, but it has not been adopted in other countries because of the expensive and complicated catenary construction and some less desirable features of the polyphase motor in traction

a) 81-p.1187 b) 81-p.1130

service.

The polyphase system affords distinct advantages for distribution in the first cost of both generating equipment and lines,. It also gives a good voltage regulation. Primary distribution in all modern alternating-current systems is either two-phase or three-phase, the latter predominating largely, Secondary distribution from transformers is either single-phase, two-wire; two-phase, three-wire, or four-wire; or three-phase, three-wires or four wires.

While the fields of alternating-current and direct-current systems for general distribution overlap each other to a large extent, it is often found that it is more advantageous to use both systems in conjunction, particularly in industrial application.

SELECTION OF SYSTEM TO BE USED

Whether alternating-current or direct-current should be used depends upon a number of conditions which are different in individual cases.

In the first place the problems of selecting either system depends upon the service desired. Electric energy may be used in buildings, I) for lighting; 2) for mechanical purposes such as elevators, pumps, fans, air compressors, ice machines, kitchen and laundry machinery, vacuum cleaners and office appliances. Or the electrical-mechanical energy may be used for electric traction or electric ship propulsion; 3) for transmission over short and long distances; 4) for heating of buildings, or electric welding or for electrochemical purposes such as electrolysis and melting in furnaces; 5) for a number of miscellaneous purposes such as telephony, telegraphy and radiotelegraphy or electrotherapi, etc..

In the second place the selection depends upon the source of energy. a) In case energy is purchased from a public utility, the system to be used depends largely upon the system available. For example, if direct-current alone is available for purchase, direct-current should be used.—Where alternating-current is purchased, this system should be used in new buildings for lighting unless the frequency is too low. Sometimes the public utility can furnish either service and it may happen that the rates for the different systems are different; in such a case the choice of system depends upon comparative costs and advantages gained by either system. Where the alternating-current is purchased it is often found necessary to convert a part or all of it to direct-current. b) In case electrical energy is manufactured on the premises it becomes necessary to select one system or the other. In some cases it may be desired to tie in with a public utility with one, two or three feeders depending upon the degree

of protection against possible shutdown, and in case the utility furnishes alternating-current, this system should be used for generation even of small quantities. Otherwise it is general practice to generate direct-current for smaller commercial buildings and the distribution is taken care of at the generated voltage.

In some cases the selection depends upon opinion or engineering judg-ment, where both systems are suitable. In other cases it is agreed that a certain system is the preferable one. In still other cases one system or the other is a necessity for engineering reasons or for economical reasons. In a great number of cases the solution depends upon which system is the more suitable for motors in individual plants, ~~and~~ but even in specific cases there is a variance of opinion. It is therefore pertinent to inquire into the application of alternating-current or direct-current for mechanical or industrial purposes.

Motor Applications. The main advantage of the direct-current motor is considered to be its adjustable speed. However,, today there are adjustable speed alternating-current motors that can be applied with equal success as compared with the direct-current motor. Therefore, a) "most motor applications can be carried out as well by alternating-current. Examples are laundry ironers, requiring wide speed range, and positive pressure blowers for tube conveyor systems which require speed adjustment to maintain required pressure. Alternating-current drives are available for these applications. Other examples are motors for forced and induced draft fans, and stoker motors for boiler plants. In some large buildings having private plants, systems for automatic maintenance of boiler pressure with changes of demand are installed. For these boiler systems alternating-current motors can be applied as well as direct-current motors."

Some engineers are strongly in favor of direct-current motors

a) 17-AE10-p.4

for industrial applications. They claim[a] that the direct-current motor is more reliable and costs less for repairing than the three-phase motor mainly on account of the very small air gap of the latter. In point of regenerative braking and freedom from power-factor troubles the direct-current motor shows to great advantage. Wiring, switch-gear and all accessories are simpler and cheaper for direct-current than for three-phase alternating-current. Also the power consumption is less for direct-current motors. For example, a certain portal crane capable of lifting 3000 kg did the same work per hour with a 22.5 horsepower direct-current series motor as with a 45 horsepower three-phase motor. The watthour consumption of the latter was 40 % higher than that of the direct-current machine and the average power factor of the alternating-current motor being 0.4 the volt-amperes supplied was 3.5 times that required with direct-current. The author[b] does not consider the cases in which squirrel-cage motors, three-phase commu-tator motors and synchronous motors with power factor correction can be used. While admitting superiority of alternating-current for high voltage transmission and admitting also the excellent performance of ~~x~~ the synchronous motor where constant speed are required , the author claims overwhelming advantages in favor of direct-current for the majority of electric motor applications where mostly variable torque is desired. However, other engineers are in favor of alternating-current for practically all purposes.

Power Contracts The problem of the power-factor was mentioned and in this connection a few remarks may be made on power contracts. Most of these have, besides an energy charge, also a demand charge which means that the customer pays a certain fixed rate according to his maximum demand. With large customers a recording demand meter is often used, but frequently it is the practice to measure the maximum demand for a comparatively short period of time by means of an indicating instrument inserted at times of greatest load and assume that the maximum thereafter is the same as that measured.

a) 19 - p.25-27 b) 19-p.25

with small customers it is common in order to save the expense of a maximum demand meter for each customer to assume that the consumer's maximum demand is a certain percentage of the connected load.

But in addition to this some power contracts have a power-factor clause which means that the customer pays an additional amount over and above the energy charge and demand charge, in case the average power-factor is below a certain definite value. For this reason it may be desirable in some cases to improve the power-factor.

There are various ways of improving the power-factor. Above all it is essential that induction motors should be selected so that they will not be underloaded. The installation of synchronous motors improves the power-factor or the improvement may be accomplished by means of static condensors. The synchronous converter has at loads above one half the rated load a very good power-factor, but cannot be made to improve the power-factor to a great extent. The synchronous motor-generator set has certain characteristics which can be used to improve the power-factor materially of the total load.

In case the power contract does contain a power-factor clause it may be necessary to ascertain the power-factor of the load using either synchronous converters or motor generator sets and make a comparative economic study of the two schemes.[a] The first cost of the converter with its necessary equipment is about 15 per cent less than the first cost of the motor generator set with its accessory equipment. The converter is considerably more efficient than the motor-generator set so the energy charge and demand charge for the former is 5-7 per cent less than for the latter. However, there are cases where the saving with the converter due to these three items is more than counterbalanced by the savings in power bills due to improved power-factor and this may justify the higher first cost of the motor-generator set.

a)17- AE10-p.6

CONVERSION OF ALTERNATING-CURRENT TO DIRECT-CURRENT

It was pointed out previously that it was often found advantageous and sometimes necessary to use both systems in conjunction in industrial plants.

It was also mentioned that a heavy direct-current can usually be more economically secured by the conversion of alternating-current than by direct-current generation and distribution, because the direct distribution of low voltage direct-current entails prohibitive losses in conductors . The general practice is, therefore, to generate and distribute high tension alternating-current and to use converting apparatus where it becomes desirable to use direct-current drives. This can be effected by using for conversion:

1) Motor-generator sets either induction or synchronous motor driven.
2) Synchronous converters with transformers.
3) Mercury-arc rectifiers.

The mercury-arc rectifiers have not yet been used for industrial purposes. as the efficiency of this apparatus for the low voltages desired in industrial plants is not much different from that of the motor-generator set.

The induction motor driven motor-generator set does not possess any special advantages over the synchronous motor-generator set and as the former has a low power factor it is practically eliminated from consideration in modern applications of more than 100 KW capacity while for less capacity the driver is usually an induction motor. Thus above 100 KW capacity the choice has to be made between the two last types of converting apparatus.

Selection of Synchronous Converters or Synchronous Motor Generator Sets

In making comparison between these two types of apparatus we will assume that the characteristics are alike in both classes of equipment

and more specifically we will first consider the most commonly used service, namely a conversion from 2300 volts, three-phase alternating-current to 240 volts, 2 wire direct-current. For this type of apparatus the approximate prices and efficiencies are[a]:

	Capacity KW	Motor-generator with Switchboard	Converter with Transformer & Switchboard
Price	200	$6200	$5400
	300	$7700	$6800
Efficiency in per cent	200	85.6	91.8
	300	86.8	92.5
	500	86.4	93.5

As regards weight and floor space required the following table gives a comparison of equivalent apparatus for 2300 volts, alternating-current supply.

KW.	Apparatus	Net weight in pound	Floor space-square foot including transformers for converters
200	Converter	13 300	52
	M G Set	11 700	43
300	Converter	12 900	55
	M G Set	16 000	49
500	Converter	20 700	73
	M G Set	24 000	66

From this it appears that the overall first cost of the converter with its accessory equipment is about 15 per cent less than the first cost of the motor-generator set with its accessory equipment.

[b]"The motor-generator set has a slight advantage over the synchronous converter as regards floor space except where transformers are needed for the motor-generator set, while for light weight of individual parts, ease in lining up and replacing armatures the advantage is with the converter."

"The transformers needed with a synchronous converter should be set close to the converter to save cable expense and minimize voltage

a)17-AE10-p.5 b)54-p.141

drop on the low-voltage side. This has two disadvantages: I) They are apt to take more space than occupied by regular power transformers which can be tucked away in small compartments. 2) The presence of 2300÷ I87 volts transformers out in the open may be construed as a greater fire risk than where lighting and power transformers of a similar primary voltage are located in separate compartments."

There are factors other than first cost, efficiency, floor space, etc., which must be considered when making a choice. The synchronous motor may be built for higher voltages than the synchronous converter thus doing away with the necessity of using transformers as figured above. Such low voltage motor-generator sets may be used for electrolytic work, arc welding, motion picture projectors, battery charging or floating on a battery, for mining, lighting and power service, etc.

The motor-generator set is superior to the converter in regard to voltage flexibility and it is often important that the voltage can be varied over a considerable range. The synchronous motor runs at constant speed and may also be used for correcting the power factor of the system to which it is connected. Power-factor correction is often an important item because public utilities give a bonus for good power factor and sometimes an additional charge for poor power factor. In this respect the synchronous motor generator set is decidedly superior to the converter.

The decision must therefore be based on a comparison between 1) the efficiency and cost of the two types of apparatus and the buildings required, and 2) the saving due to power factor correction of the motor generator set and also 3) whether it is desirable to maintain an electrical segregation of the alternating-current and the direct-current systems. The first consideration would favor the converter the two latter the motor-generator set.

For heavy industrial service it appears[a] from the ratio of installed capacity that the more advantageous operating characteristics of the latter is valued higher than the lower price and better efficiency of the converter, whereas for railway and lighting service, where space is a material item the proportion of installed capacity is 2.5 KW of converters for each KW of motor-generator set.[b]

a) 27-p.677 b) 28-p.398

COST OF ELECTRICAL MACHINERY

Several references have been made to special cases of the relative cost of machinery for alternating-current and direct-current service. Some references will here be given to a general tabulation of the cost of electrical machines.[a] A general comparison must include both type and capacity and speed as the latter is an important factor both as to cost and weight. For example, a one horse-power motor running 2000 revolutions per minute is much cheaper than and about one-half as heavy as a corresponding motor at half the speed. The rational way to tabulate either cost or weight data is, therefore, in terms of dollars or pounds versus kilowatt divided by speed. The ratio KW ÷ R P M is really torque and of any machine it can be said that the greater the torque the greater the necessary size, weight and cost.

COST IN DOLLARS

KW ÷ R P M	0.001	0.01	0.1	1.0	10.0
Direct-current generators and motors	$ 85	280	1150	5500	-----
Induction motors	$100	260	850	3500	-----
Alternators	---	---	1200	4600	16000

WEIGHT IN POUNDS

KW ÷ R P M	0.001	0.01	0.1	1.0	10.0
Direct-current generators and motors	130	810	4200	22000	110 000
Induction motors	80	510	2800	15000	81 000
Alternators	130	810	4200	20000	90 000

It is seen that for machines of small torque the direct-current machines are cheaper than the alternating-current machines, but in most cases the reverse is true.

As an example of how this may work out let us consider a study made to determine best equipment to give lowest cost in a particular industrial plant.[b]

a) 9-p.746 b) 10-p.996

Equipment of an Alternating-Current Proposition

I - 500 KW four valve prime mover, a.c. generator and exciter	$22 200
I - 300 KW four valve prime mover, a.c. generator and exciter	I7 I00
I - I00 KW motor - generator set(for cranes & special service)	3 000
Cost of power plant	I67 250
Total	209 550

Equipment of a Direct-Current Proposition

I - 500 KW four valve prime mover and d.c. generator	26 700
I - 300 KW four valve prime mover and d.c. generator	20 000
No motor-generator set	------
Cost of power plant	I7I 750
Total	2I8 450

Of course, to make a complete comparison of economics of different schemes it is necessary also to include the cost of the distribution system, cost of maintenance, depreciation ,etc., and to consider special advantages arising from the adoption of either system. But all such considerations are very different for every individual case.

[illegible]

INDUSTRIAL APPLICATIONS

SELECTION OF ELECTRICAL SYSTEM FOR IRON AND STEEL WORKS

General. For steel mills electric power is used both in the form of alternating-current and direct-current energy. In most cases the practice is to have three-phase generation and transmission of about 3000 volts because it is the best and cheapest system. Alternating-current is then used directly for a relatively few large, steady running motors and in some cases for electrothermal applications. In the latter case the tendency is more and more towards abandoning the arc furnace and use induction furnaces instead. However, special precautions must be taken for the correction of power-factor; for example, the leads to the furnace are run so as to give minimum self-induction and the transformers are constructed especially with a view of reducing the no-load current. Power-factor correction for the plant as a whole is often accomplished by means of synchronous motors or static condensers.

Alternating-current is also used for the conversion to direct-current for motors for severe and intermittent loads such as reversing blooming mill drives which are invariably operated as a unit with a special motor-generator set.

Direct-current is used to operate a proportionately large number of relatively small auxiliary drives and magnetic equipment for lifting and transporting of materials.[a)] No plant would be complete without such equipment and therefore direct-current cannot be cut out entirely from the plant.

Generation and Distribution.

Three schemes for generating and distributing electricity in a steel plant can be considered.

I) Generate and distribute direct-current at 500 volts or less. This

a) 27-p.672

system must be ruled out because it is too costly to transmit this form of energy to large motors even over a distance of only 750 yards. 500 volts is the safe limit that can be used for most auxiliary drives Therefore, for the supply of electrical energy the easy flexibility of voltage afforded by alternating-current transformers is essential.

2) Generate and transmit high tension alternating-current using transformers and all motors running on alternating-current. The special advantages of direct-current auxiliary drives make this a less desirable scheme.

3) As 2) but use alternating-current for all steady running motors and convert to direct-current for severe and intermittent load and special service.

a)"The approximate ratio of capital expenditure for a power station equipment based on 3000 KW units and consisting of steam turbines, condensers and generators together with static transformers or rotary converters of say 50 % of the generator output would probably work out approximately as follows:

		Per Cent
Scheme I a) Geared direct-current 500 volts single generators and steam turbines 3000 ÷ 350 r.p.m.	equals	100
b) Geared direct-current 500 volts double generators and steam turbines 3000 ÷ 600 r.p.m.	equals	91

In this scheme no converting or transforming equipment would be necessary.

		Per Cent
Scheme II Steam turbines 3000 r.p.m. and alternating-current three-phase 3000 volts generators complete with rotary converters rated at 50% of generator output	equals	98

a) 25- p.594

Per Cent

Scheme III Same as II except using static transformers equals 82.5

The last scheme is cheapest and is claimed to be the best scheme to adopt from an operating viewpoint, the author referred to being in favor of alternating-current. On the other hand, another author[a] claims that the excess cost of rotaries and their transformers as compared with transformers alone is balanced first, by the fact that the rotaries improve the power-factor from about 0.7 to 0.9 or higher and so reduce the cost of alternators and the feeders, and, second , due to the higher efficiency of the direct-current motors resulting in a smaller peak load and so reducing slightly the capacity of the main generating plant required.

An expensive part of a steel works' electrical scheme forms the main feeders and distribution cables. It is therefore important to use as high voltage as feasible for the motors and for the application of electrically produced heat for the melting and refining of steel. This latter service calls for heavy supplies of current by step-down transformers.

Comparison of Motors Probably 25 to 30 per cent of the plant's auxiliaries can be arranged for alternating-current motor drives. The modern alternating-current motor is simple and reliable and is fairly efficient. For the larger sizes (used in steel plants up to 4000 horse power) it is also the cheapest with the exception of heavy special type of machines. A comparison of cost of the average size steel work's motor would be as below:[b]

	Per Cent
Standard direct-current shunt machines equals	100
Standard alternating-current slipring machines eq.	92
Standard alternating-current squirrel-cage machines	74
Special railway type direct-current mill motor eq.	91
Special railway type alternating-current mill motor	100

a) 26-p.672 b) 25-p.594

A practical comparison of alternating-current and direct-current motors was made[a)] by hoisting a weight of ten tons ten feet by a 44 volt 30 horse-power series wound direct -current motor until 5 kilowatt hours were consumed. The direct current motor was then replaced by a 32 horsepower 440 volt three-phase 50 cycles slip ring induction motor and the same weight again lifted until 5 kwhrs had been consumed. In both cases the same section and length of cable was used.

		A.C. Motor	D.C. Motor
Units consumed	Kwhrs	5	5
Number of hoists		40	45
Units per hoist		0.I25	0.III
Time per hoist	seconds	26	22
Overall efficiency	per cent	68	76.3

The alternating-current motor has lower efficiency due to its poor starting qualities and its rapid fall of efficiency as it approaches half load. The author referred to considered the reliability of a direct-current motor higher than for an alternating-current motor because of its larger air gap between armature and field poles and therefore less risk of serious trouble due to wear of bearings. Commutators are usually held up as a weak point in direct-current motors, but provided suitable brushes are used, the failure of a motor due to its commutator is remote. The direct-current motor requires more careful attention than slip ring motors, but it is absolutely reliable in the author's opinion and as far as adaptability is concerned it far outruns the alternating-current motor.

Conclusion Due to the varied service required in iron and steel works it is almost a necessity to use both systems in conjunction, but each system serves its special purpose within the plant. To reduce the cost of generating and distributing the electrical energy it is desirable to operate as large a number of drives on alternating-current, but some very important main drives and a great number of auxiliary drives must be operated on direct-current.

a) 26 - p.672

ELECTRIC POWER IN MINES

The four most important loads in mines are pumping, air compression, ventilation and winding.[a]

Pumps and Compressors These equipments can generally be better operated by alternating-current motors as they run at constant speed. Some pumps ,like elevator pumps, require variable speed, but it can be obtained by alternating-current motors. For compressors where occasionally variable speed is important, direct-current may be desirable but in mines they are usually run on alternating-current system. Alternating-current motors are extremely substantial and reliable and are generally less expensive than direct-current motors. Up to I50 horsepower, squirrel cage motors are satisfactory; above I50 horsepower, slip ring motors are preferable. High efficiency and fairly high power factor are obtainable with four pole and two pole machines of all sizes. Only in exceptional cases need synchronous motors be considered for pumping, despite the fact that power-factor correction has become of great importance. Phase advancers, synchronous and static condensers have all been tried, but the best results have been obtained from synchronous motors driving the large units.

Ventilating Fans provide an almost uniform load and if they are large enough to be driven by synchronous motors they are helpful for power-factor correction. Usually the speed is too low and they are therefore driven through reduction gears, or by belt or chain drive, which provides for progressive increases in speed. The initial cost of a variable speed motor and starting gear is I0-I5 per cent greater than that of a directly coupled synchronous motor. The gear drive gives a rather good efficiency when it is new but when it begins to wear, the balance is in favor of direct-coupled motors. This latter is also somewhat less noisy, but usually this makes little or no difference.

a) 29 -p.242

Alternating-current motors are more noisy than direct-current motors, although the noise can be minimized by special motor construction and vibration-proof mounting.

<u>Elevators, Lifts and Winders.</u> The chief electrical problem to be solved for a mine is the operation of the cage, and is a choice between the so-called Ward Leonard system and a three-phase alternating-current motor with rheostatic control in the rotor circuit.

Before this is considered, as applied specifically to mines, let us first consider the operation of elevators in general. The earlier elevators were of the direct-current type, due primarily to the fact that alternating-current motors were not very well developed and that the direct-current motor was the only type which even approached the requirements of elevator service where the drum shaft usually runs 28-75 revolutions per minute.

The typical requisites[a] for an elevator drive are I) reliability and safety, 2) good speed control, 3) quickness of operation, 4) smoothness of operation, 5) low power consumption, 6) smooth load demand curve for varying speed. To-day all types and speeds of elevators may be run from alternating-current motors, but on account of their high speed, it is either necessary to use gears or to convert to direct-current. The direct-current motor is very well adapted for low speed elevators without gears as the motor speed is generally around 65 revolutions per minute and seldom reaches I50 r.p.m. Therefore, where elevator service is required in a building located in a metropolitan or other district served by direct-current, this system should be used for direct elevator service.

Where only alternating-current is available the elevator can either be run by alternating-current motors or by a direct-current motor driven by a motor generator set. In the first case low speed elevators can be operated by the "single-speed" type of alternating-current elevator

a) 18- p.109

motor. While the alternating-current induction motor is the most reliable of all types it is not quite suitable for elevator operation without special precautions, because it is inclined to be noisy and the elevator shaft increases the noises by producing an organ pipe effect. High speed elevators, 500 r.p.m. or over, will usually be run on conversion. This second case is the choice where the highest degree of service is desired, both as to speed and accurate floor levelling. Where the power is converted to direct-current, speed control can be obtained either by series resistances, by coupling generators in series for varying the voltage or by the Ward-Leonard control system. With this latter type of control, a direct-current elevator motor is operated by a motor-generator set, and the speed is controlled by varying the generator voltage. "Only the field current of the generator need to be handled by the control contactors, which greatly simplifies maintenance work, and reduces maintenance expense, in that the contactor-tips last longer and are considerably cheaper."[b] This system gives smoother and more accurate control, greater capacity of service and tends toward greater continuity of service and in many cases less power consumption than the older direct-current rheostatic control.

Turning our attention again to the special conditions met in mines, a mathematical investigation[c] has shown that the Leonard system is preferable if $B = (MS) \div (Q T^2)$ exceeds 0.2[illegible]-0.25 and is indispensable if it exceeds 0,3, where

M is equivalent mass equals weight in pound ÷ gravity coefficient
S is depth of shaft in feet
Q is useful load plus friction, in pounds
T is net time of wind in seconds

[a]The advantages peculiar to the Leonard system in mines as compared with the induction motor system with rheostatic rotor speed control are 1) facility and accuracy of operation; the speed is very well defined and independent of load; and

a) 23-p.256 b) 18-p.109 c) 29-p.242

regenerative braking can be used during descent of loads. 2) No material load variation on the supply system. The starting peak of the Leonard system is much less sharp and of shorter duration than the direct three-phase system and as the emergency brake may operate quite often on the latter system due to its cruder speed control, this also may give load peaks on machines and cables. 3) The Leonard system is more economical in operation than other systems. A special case is investigated as follows:

		Leonard System	Three-phase system
First cost of equipment	francs	300 000	I40 000
Energy consumption	Kwhrs	797 340	I039 966
Interest 6 per cent		I8 000	8 400
Amortization 4.296 %		I2 888	6 0I4
Cost of Energy		II9 600	I55 995
Total	francs	I50 488	I70 409

In a subsequent article another author[a)] refutes these figures and claims that the difference in power consumption is not so great. He recognizes that the Leonard system is superior to the induction motor in flexibility and precision of control, but this superiority is less marked nowadays than it was previously and the induction motor is amply capable of rendering the service required in mines; and from the point of view of sturdiness and first cost, it is decidedly superior. The author revises the figures based on certain modifications and finds:-

		Leonard system	Three-phase system
First cost of equipment	francs	300 000	I64 000
Energy consumption Kwhrs	appr.	900 000	942 000
Interest 6 per cent		I8 000	9 840
Amortization 4.296 per cent		I2 888	7 045
Cost of energy		I35 805	I42 940
Total		I66 693	I59 825

These figures are quoted to show how careful one has to be in relying on estimated costs even for a specific case. That the Leonard system is preferred for mine service, at least in France, is proved by the fact that for the electrification of the mines in the devastated area, 85 % of the machines ordered were of the Leonard type.[b)]

a) 22-p.376 b) 24-p.124

Summing up the merits of the two systems of control the advantages of the alternating-current system are simplicity, low cost, less space occupied and no stand-by losses; and for the Leonard system, flexibility, ease of control, complete automatic control if desired, lower wear and tear of brake gear, peak loads of system gradually applied. For high speeds the Leonard system is usually the more efficient, but for heavy loads from deep shafts at low or moderate speed the alternating-current system is more economical, and even in these cases the saving is sometimes insufficient to outbalance the technical advantages of the Leonard system.

ELECTRIC POWER IN ELECTROCHEMICAL INDUSTRIES a)

<u>General</u> The most important electrochemical industry is the electrolytic production of aluminum and this is also the classical example of applying electricity for the cheap production of certain metals which could be made by other means only at great expense. As very large quantities of electricity are used, it is absolutely essential that the power is available at the lowest cost and therefore the electrolytic plant is usually located in close proximity to a hydroelectric plant. The first installations were made by means of direct-current because this system was technically further advanced than the alternating-current system and as the installations were of relatively small size, no serious troubles were encountered, because the electrolytic installation could be made directly in the generator room. The practice of the Southern Aluminum Co. and the French concerns is still to generate and distribute direct-current, but the practice of the Aluminum Company of America is to generate and distribute alternating-current and transform it by means of commutating machines to direct-current of the low voltage required (sometimes 2-3 volts). The same tendency to adopt the latter system seems to prevail in other installations made during and after the war and it would therefore not be without interest to study the reasons for this change of practice.

<u>Location of plant</u> Evidently the choice of system depends primarily upon the relative location of the hydroelectric generating plant and the electrochemical plant because of the great amount of power to be transmitted. As long as the plant is small and the few employees can be housed in special huts erected near the plant, this can naturally be located as near to the generating plant as is physically possible.

a) 30 - p. 822

But the modern factory cannot always be placed quite close to the generating station, the location of which is pretty nearly fixed by the fall of water. A factory must nowadays be placed in accordance with railroad facilities in order to obtain easy disposal of products and convenient methods of getting equipment and materials.

The employees must live near the factory either in an already existing town or in a settlement built up by the industry but having reasonable access to the outer world.

For those reasons it is generally desirable to locate the factory at a certain distance from the hydro-electric station and the problem of transmission of energy becomes of major importance.

Comparison of systems The author of the article[a] referred to at present, examines the losses due to transmission of direct-current over certain distances. For example, he finds that at 240 volts the loss over a distance of 300 yards is 7.9 per cent at full load, 5.9 per cent at ¾ load and 3.9 per cent at half load.

The next problem is to compare the efficiencies of the machines of the two systems. The author finds there is an advantage in per cent efficiency in favor of direct-current dynamos over the combinations as listed:

	I/I load	3/4 load	I/2 load
Alternators-transformers and simple commutator machines	3.2	4.2	5.9
Alternators-transformers and commutator machines with booster	4.0	5.2	7.I
Alternators-Synchronous converters	6.9	7.8	9.9
Alternators-asynchronous converters	8.8	10.2	I2.4

The most practical solution for this particular industry is the second one, so let us include in this case the transmission losses mentioned above assuming no such losses for the high voltage alternating-current transmission. In favor of direct-current dynamos there is an advantage in per cent at full load- 3.9, at 3/4 load - 0.7, and at ½ load + 3.2% that is the advantage has more than disappeared.

a) 30 - p.822

Moreover, a distance of 300 yards is generally not enough space for facilities for transportation and fabrication and as the practical limit for a direct-current dynamo is of the order of 5000 KW, whereas alternators can be built very much larger, the result is that for larger installations the efficiency of the alternating-current system is considerably larger than that for direct-current system even though the energy does not have to be transmitted over a great distance.

As regards the cost of the machines, the alternators are considerably more expensive than direct-current machines. However, this is offset, because the large alternators require much less space and consequently less costly buildings than the corresponding number of smaller direct-current machines, so for large plants the cost of installation is of the same order for the two systems.

There is a further advantage of generating alternating-current for such a plant and that is the possibility of tying with the general power transmission system thus insuring greater reliability of power supply.

Conclusion We have seen that the alternating-current system has considerable advantages over the direct-current system for an electrolytic plant even in the case where the factory can be located in the immediate vicinity of the water power source.

It is interesting that the author of the article referred to, who is a noted French engineer, has come to this conclusion, since in general Frenchmen are much interested in and in favor of the direct-current system. A notable example of this favor on the part of Frenchmen for the direct-current system is the article referred to in reference #15. The author there persists in regarding adjustable speed alternating-current motors as disguised direct-current motors.

ELECTRIC DRIVE IN TEXTILE INDUSTRIES[a]

There are certain peculiarities with spinning and weaving mills which make the application of electric drive rather special and the problem of selection of system very important. There is in such plants a large number of weaving looms and spinning frames which have a very variable load but which require the most regular drive in order to minimize the breakages of threads. The speed should be as high as possible in order to insure maximum output of the frame, but as the number of breakages of thread which occur increases rapidly beyond a certain speed limit, any irregularity of speed will mean that the average speed must be chosen at a value lower than if the motor speed were constant. The irregularity of speed results from a variety of causes such as variations of load and temperature, slip in belts and oscillations in the line shafting.

After some preliminary tests[b] with direct-current motors an early decision was made in favor of the three-phase drive because in most cases textile machines do not need any great range of speed regulation during operation and because in others, as for instance, on weaving looms direct-current motors without clutch coupling is not practicable. To this rule ring spinning machines are an exception, for they require a regulation of the working speed in order that the full output of the machine may be obtained. This regulation is easily possible when three-phase commutator motors are used by the employment of a brush shifting arrangement. Their disadvantage, their series characteristics, does not generally make it advisable to replace them by direct-current shunt machines for ring spinning machinery, as the installation is made considerably more complicated and expensive thereby. "The advantage of driving spinning and doubling frames by slipring motors lies in the fact that each motor can be directly coupled to the frame with a rigid coupling.

a)31 - p.225 b)20 - p.235

It has, however, other serious disadvantages. Its efficiency is somewhat lower than the squirrel cage motor and it is more liable to break down owing to the rotor carrying an insulated winding. The sliprings and the brush gears are also undesirable because of the danger of fire on account of the cotton fibres. The motor occupies slightly more room than the squirrel cage type. Owing to the disadvantages, this type of motor is not used to any great extent for driving ring and doubling frames." a)

The squirrel cage motor is from the point of view of simplicity and reliability pre-eminently the best for driving cotton frames. It has a speed independent of the load. From this point of view this motor cannot be improved upon. Its temperature variations are also small. The motor is also satisfactory from the point of view of power-factor and efficiency. Cost of maintenance, easy cooling, absence of vibration and small space occupied are other points in its favor. As the motor can be made dust-proof it is well protected against the entry of dust and cotton fibres and so the danger of fire due to the motor is practically eliminated. Any alteration in speed can be affected by changing the gear wheels, and the motor is reasonably low in cost. "Its sole disadvantage is that it takes a large current from the line at starting. Various methods are employed to obviate this; for example, the motor may be started by means of the usual "star-delta" starter, "star" at starting, "delta" at running." a)

"The simple squirrel cage motor, either direct-coupled to the tin roller shaft or driving the tin roller shaft through spur reduction gear or chain cannot be excelled when the squirrel cage motor is mounted on a stool on the floor and bolted rigidly to the frame end." b)

a) 34- p.239 b) 32- p.232

Conclusion "Not all forms of electric drive are equally satisfactory. Except in certain cases it is now recognized that to drive each machine by its own motor is more efficient and gives better results than when group driving is employed. But the direct-current motor is not suitable on account of its characteristics, and its speed alters with its temperature. The variable speed alternating-current motor is an unnecessary expense except in special cases and it is beginning to be recognized that the driving of the textile machinery is especially the field of the induction motor. It has the speed and temperature characteristics which are required; it gives a practically constant torque under the varying loads met with; it requires little maintenance and it is cheap. The only disadvantage that it takes a large current at starting can be overcome by starting devices or it may be allowed to run up to speed before it is switched on to the machine." a)

a) 32 - p. 225

SUMMARY OF APPLICATION OF ALTERNATING-CURRENT AND DIRECT-CURRENT.[a)]

ALTERNATING-CURRENT.	DIRECT-CURRENT.
Generating Stations.	**Generating Stations.**
Turbo-alternators of all sizes up to I50 000 KW and pressures up to I3 500 volts	Turbo-dynamos of small capacities up to 2000KW and pressures up to 5000 (or 7500) volts
Transmission.	**Transmission.**
Raising and lowering pressures by means of static transformers up to 220000 volts.	High pressures obtained by series coupling of generators. Conversion to alternating-current by means of motor-generators or the transverter.
Steel armored cables three-phase up to 50 000 volts, single-phase up to I32 000 volts.	Steel armored cables up to I00 000 volts.
Overhead lines pressures up to 220 000 volts.	Overhead lines pressures possible up to 300 000 volts.
Advantages: Static transformers used for industrial and lighting purposes.	Advantages: Capacitance and reactance of line are not harmful. Only two wires necessary. No stability troubles. No telephonic interference.
Disadvantages: Capacitance and reactance of lines necessitate the use of synchronous condensers. Stability troubles. Telephone interference.	Disadvantages: Line losses constant. Poor efficiency at light loads. Motor-generator sets used for obtaining industrial pressures.
DISTRIBUTION AND APPLICATION.	**DISTRIBUTION AND APPLICATION.**
Lighting. Only frequencies above 25 cycles acceptable.	Lighting. Used much in metropolitan districts.
Traction. Only trolley used. Three-phase requires two overhead trolleys. Pressures up to I0-I5000 volts. Frequencies up to 45 cycles. Single-phase requires only one trolley. Pressures up to 22 000 volts and frequencies I6 -2/3 or 25 cycles.	Traction. Trolley or third rail. Tensions up to 3000 volts. Substations for conversion of three-phase distribution current by means of synchronous converters or mercury-arc rectifiers. In case of the direct current series system by means of motor-generators.
Advantages: Substations with static transformers and widely spaced	Advantages: Regenerative braking for down-hill runs and for stopping.

a) IF p. 1235

Disadvantages: Regenerative braking complicated for single-phase. This system also requires special generating stations.

Disadvantages: A large number of substations required.

Factories. All ordinary motors with reasonably constant speed.
Variable speed motors uneconomical and unsatisfactory.

Factories. All ordinary motors with constant or variable speed for accurate speed regulation.

Mines. Induction motors for all usages. Slip-ring motors for ventilators or special drives.
Synchronous motors used for power-factor correction.

Mines. Ordinary drives used in connection with converters or motor-generator sets if necessary.
For hoisting machinery the Ward-Leonard system.

Metallurgy. Alternating-current for small motors.
For laminating machinery alternating-current little used.

Metallurgy. Direct-current for a number of auxiliary drives and for some important service in steel works. For laminating machinery direct-current is preferable.

Electro-Metallurgy. Arc furnaces of all capacities, single-phase or three-phase.
Induction furnaces. High frequency furnaces.

Electro-Metallurgy.
Only arc furnaces.

Electro-Chemistry. Alternating-current unsuitable for electrolysis.

Electro-Chemistry. Electrolysis by direct-current at low pressure.

Electro-culture. Alternating-current for all motors. Ease of distribution.

Electro-culture. Direct-current for all motors.

Hoists and Elevators. Three-phase current used but less accuracy of service.

Hoists and Elevators. Direct-current is preferable.

Miscellaneous. For telegraph, telephone and signals alternating-current little used.

Miscellaneous. For telegraph, telephone and signals direct-current almost always used.

GENERAL CONCLUSION

The question of interchangeability of motors for the different systems may sometimes be of importance for certain types of single-phase alternating-current motors can run equally well on direct-current. This is sometimes used on the electric traction systems, for example, on the New York, New Haven and Hartford Railroad. "Within certain limitations direct-current series motors will run on alternating-current provided sufficient voltage is applied to the terminals. But satisfactory operation depends upon a great many factors.

When operating on alternating-current a certain portion of the line voltage is absorbed by the resistance drop in the field and armature windings as in the case of direct-current. But in addition to this, there is an induction voltage drop which absorbs still more of the applied line voltage leaving less available for producing torque and speed. Consequently, the motors have a marked tendency to run at lower speed on alternating-current than on direct-current. This inductive voltage drop increases with the frequency of the alternating-current supply and consequently less useful voltage is available on high frequencies than on low frequencies.

Some of these features can be eliminated by special design of the motor, but it is obvious that high-speed direct-current motors will operate more satisfactorily on alternating-current than those wound for lower speeds. Some direct-current motors designed for direct-current will not start on alternating-current, because the combined voltage drop is so great that insufficient active voltage is available to produce enough torque to overcome the friction." [a]

A marked advantage of direct-current is the possibility of storing the energy in accumulators. This is not possible with alternating-current. There are many applications of accumulators; for example, in mines they are used for traction and the electric portable lamps have

[a] 34A - p.237

considerably increased the output per miner and at the same time increased the safety against explosions.

Accumulators are used in another field of traction; namely, for electric automobiles and it is interesting to see that despite the continuous perfection of the explosion motor for automobiles, the electric automobiles are still used to some extent, perhaps mainly on account of their ease of control. It is not at all impossible that accumulators may in the future be used to a great extent also in locomotives for traction over long distances. They are used now, for example, for the starting of oil-electric locomotives.

To sum up the relative merits of the two types of motors it may be said that the direct-current motor requires frequent attention to the commutating gears to avoid sparking. Direct-current motors can be economically subjected to speed regulation over a wide range and, perhaps most important of all, for example, in central stations, they can be run off a battery in times of breakdown or other emergencies.

"The greatest disadvantage of alternating-current induction motors lies in the fact that speed regulation is not an economical proposition. Of course, the speed of a slipring motor can be varied by varying the resistance in the rotor circuit, but this is a very wasteful method, and the system of having a controller to alter the connections of the stator windings and so alter the number of poles, is only suitable for three or four speeds at the most. Variable-speed motors working on the "cascade" principle[b] might be used, but these give only a limited number of speeds which are fixed by the number of poles.

On the other hand, in the case of pumps and fans, which form a very large proportion of, for example, steam power station auxiliaries, the output can be controlled by throttling; that is, by control of dampers or valves."[a]

a) 34-p. 829 b) 81-p.559

Thus where it is necessary to obtain a fine and precise speed regulation one must take refuge to direct-current and if necessary convert alternating-current in the most economical manner.[a)]

When first conversion has been decided upon it is often found desirable to use direct-current on a very large number of auxiliaries.

Therefore it must be concluded that direct-current is an inddispensible supplement to alternating-current because it can redress some of the inconveniences of alternating-current in regards to inflexibility for industrial application.

a) 15 - p. 1235

CHAPTER 2

GENERATION AND DISTRIBUTION

GENERATION AND DISTRIBUTION

Generating electrical energy The modern generating station has come to a point of refinement and economy where great improvements cannot be expected in the near future. Yet the thermal efficiency of converting coal into electricity is rather low, because the heat energy in the coal has to be converted into energy in the form of steam under pressure and this energy must in turn be converted into mechanical energy by means of a steam engine obtaining its energy from the heat drop available by the expansion of the steam between two pressures. First then the mechanical energy is available for producing electrical energy . All these processes entail losses and even considering a perfect engine working on the ideal Rankine cycle the possible theoretical thermal efficiency is not higher than 40 per cent and for actual steam machines the efficiency does not exceed 30 per cent.[a] The thermal over all efficiency of a modern generating station is at best 22 per cent,[b] but before the consumer gets the electricity it must pass the distribution system which may give an additional loss of 15 per cent. Thus the consumer obtains 22 (1- 0.15) that is less than 19 per cent of the heat value in the coal.

Now, why is this economical? How can for example electric heat ever compete with heat produced on the spot? The answer is first that it cannot yet. But it must be pointed out that there are considerations other than purely economical ones. In the first place electrical heat is the cleanest medium for heat, due to the absence of fumes and gases and this may become very important in large cities. In the next place it lends itself to the most perfect control of the temperature and third the efficiency of converting electricity to heat is of the nature of 100 per cent. In the fourth place the individual consumer

a) 81-p.737 b) 7-214

must have high grade coal for which he must pay two or three times the price of the lower classes of coal which the large generating stations can use with advantage.

When high grade coal becomes more scarce and more expensive this part may become very important and, furthermore, the cost of maintenance and of operation of the local plant is proportionately much higher than for the large central plant.

It must also be remembered that the consumer has the electricity for many other purposes: for light with an efficiency of about 100 per cent and for mechanical purposes with an efficiency of from 80 to 90 per cent, and for such purposes the local plant cannot compete with the large high-efficiency central plant.

Location of steam plants. An important consideration for the location of large generating plants is the coal supply. By locating the plant on a river or at tide-water the coal may be supplied by barges which is much cheaper than by railroads. But why cannot big plants be built at the coal mines? That is because the modern steam plant must have an abundant supply of cold water in order to be operated efficiently and such a supply is usually not available at the mines. The water is used for condensing the steam whereby more power can be secured than without condensation. Wells may possibly supply the required water; or, failing this, cooling towers may be erected; but it is usually much cheaper to ship coal from the mines to the steam plant located at a sufficiently large body of water than to provide water at the mines because the weight of water used for condensing purposes is from 400 to 500 times the weight of coal burned in the boiler furnaces. For this reason the presence of a suitable water supply determines the location of the steam plant. Generating stations should not be located too far from the place of utilisation as the cost of transmitting electrical energy over long distances is so high, that beyond a certain distance it becomes

more economical to transmit the energy in freight cars in the original form of coal.

<u>Hydro-electric plants.</u> There is a common notion among the public that the development of the water-power resources will provide a plentiful and cheap supply of electric energy. This is a very erroneous idea, since in the first place the available water power is not nearly sufficient to cover the demand and it has a seasonal character, both of which conditions require that the hydro-electric stations must be backed up by large steam plants. There are very few developments where a relay station, steam, gas or oil plant, owned either by the seller or by the buyer of hydro-electric energy, is not almost essential. In the second place development of hydro-electric stations is extremely expensive and only a very limited part of the total water-power resources can at present be developed economically. The economical development of a water-power proposition depends upon the available power in the river, the size of the market and the distance to it, and the degree to which the hydro-electric power is to be utilized. A very large amount of water falling a considerable distance is required to produce the same amount of electrical energy as one pound of coal.

[a] The cost of hydro-electric plants vary greatly, depending first on the physical characteristics, namely the head of the water, the distance from existing railways, the geological formation, the availability of rock, gravel and sand, the difficulties of handling, the climate, the character of the flow in the river; secondly, on the price of labor, on the lands to be acquired, on existing developed rights which will be destroyed; thirdly, upon the prevailing price of material; fourthly:- upon the ~~cost~~ amount of the contract and the ~~amount~~ cost of money.

Another very important consideration is the transmission plant. Enormous quantities of water run daily to waste because the distance from the water falls to the markets of electricity is beyond economic.

a) 41- p.35

transmission range.

[a]Some cost data (Spring of 1921) of a fairly average condition of a moderately sized plant (25 000 KW) may be of interest:

ITEM	Per Cent of Total Cost	Cost per kilowatt
Property	19.3	$48.00
Dam	11.6	29.00
Canal	42.3	105.20
Power house and foundations	9.6	24.00
Equipment	17.2	42.80
Total	100.0	$249.00

Note that the cost of the dam and the canal represents more than one half of the total cost . The cost per kilowatt of hydro-electric power is usually more than double the cost of steam-electric power, and furthermore the steam relay stations required to supplement dry-weather flow, will add 30 per cent more to the total cost.[a]

Cost of electric service The problem of determining the rates for electric service is very complicated, if it is to be done exactly. There are two theories for rate making, namely the value-of-service theory and the cost-of-service theory.[b] The former is the older one and is based on what the traffic will bear and competition allow. This was in the days before regulation. The latter theory is based on the principle of equal rate for same service and the rate covering the cost of service, this cost including a reasonable return on the investment. The rate usually consists of a demand charge and an energy charge, or of "fixed charges" and "running charges". The former includes all capital charges, management, most of the repairs and maintenance cost plus a small portion of the coal. The total fixed charges of the system divided by the number of kilowatts of maximum demand gives the "fixed charge per kilowatt of maximum demand."[c]

a) 81-p.843 b) 81-p.1998 c) 7-p.214

The "running charges" depend on the number of units sold and they amount to the cost of coal plus a small portion of wages, etc. plus losses in the system. The total cost of supply is made up of the following elements of cost: I) power station, 2) main transmission, 3) secondary transmission, 4) transformation or conversion, 5) distribution, 6) metering and collecting. The latter cost may be 22 sh. 6 d. per meter, to quote an English source[a), and has little influence on the average cost in the case of comparatively large consumers, whereas for house service which may only take I00 kwhrs per annum this cost alone represents ~~a cost of~~ 2.7 d. per kwhrs. This explains why a public utility in some cases charges 6 d. per kwhr and in other cases less than 0.5 d. per Kwhr. In the following the cost for metering is not included.

Let us consider a generating station costing I5 l per kw to build. The annual charges on the station are taken as 2 l. I7 sh. 3 d. per kw plus 0.I25 d. per kwhr.

This cost is increased in main transmission and transformation to 3 l. 9sh. 6d. and 0.I29 d; the secondary transmission brings this up to 3 l. I5sh. and 0.I39 d; after passing through the substations the cost of low-tension direct-current supply becomes 4l. I9 sh. 5d. and 0.I47d; and the distribution losses and charges on low-tension direct-current mains bring the total cost to 6 l. 9sh. 2d. per kw demand plus 0.I59 d. per kwhr at consumer's premises. The corresponding figures for alternating current are also given in the summary below and total 5 l. I3 sh. IId. plus 0.I50 d.

a) 8 - p.200

In this summary[a] HT means high-tension; LT low-tension; AC alternating-current; DC direct-current; L pounds, sh. shillings, d pence.

	Type of supply	Fixed charges per Kw. Cost L.	sh.	d.	+ Running charges per Kwhr. d.
I. Power station terminals	HT.AC. 33 000 Volts	2	I7	3	+ 0.I25
2. Main substations	HT.AC. 6 600 "	3	9	6	+ 0.I29
3. Distributing substations	HT.AC. 6,600 "	3	I5	0	+ 0.I30
4. Utility substation	LT.AC. 230 & 400 volts	4	2	5	+ 0.I39
5. Consumer's substation	LT.AC. 400 "	4	5	0	+ 0.I39
6. Consumer's premises	LT.AC. 230 & 400 "	5	I3	II	+ 0.I50
4.A Utility substation	LT.DC. 220 & 440 "	4	I9	5	+ 0.I47
6.A Comsumer's premises	LT.DC. 220 & 440 "	6	9	2	+ 0.I59

When the load factor is assumed the average cost per kwhr can be found. The load factor is the ratio of the average power to the maximum power during a certain period of time. Experience has shown that the cost per kwhr varies inversely as the fourth root of the load factor[b]. In the different cases as above the average cost in pence per kwhr not including metering charges will be[a]:

Case	Load factor in per cent 10	20	30	40	50
I	0.9I d.	0.52 d.	0.38 d.	0.28 d.	0.23 d.
2	I.08	0.60	0.45	0.32	0.25
3	I.I5	0.65	0.47	0.34	0.27
4	I.28	0.7I	0.52	0.36	0.29
5	I.30	0.72	0.53	0.37	0.29
6	I.7I	0.93	0.67	0.46	0.36
4 A	I.50	0.83	0.60	0.42	0.33
6 A	I.92	I.04	0.75	0.5I	0.39

It is seen that the cost of direct-current supply is materially higher than that for alternating-current supply.

Economics of distribution system. The economic solution of distribution problems is of great importance since the point is now reached where the cost of producing the electricity has decreased until it is but a small portion of the total cost, whereas the cost of distribution has risen very rapidly. To illustrate the great influence which

a) 8-p.200 b) 81- p.910

the cost of distribution has on the total cost of power delivered to the consumer the table below gives the relative elements of costs:

	Generation	Transmission	Distribution
Operating costs	100 %	59 %	178 %
Maintenance	100	245	470
Fixed charges	100	33	133
Depreciation	100	150	400

The investment in the distribution system is a large part of the total investment in the system. In some systems it may be 30 per cent in others 60 per cent. One may divide the distribution system in three parts, 1) transmission, 2) substations and 3) local distribution. To take an actual example[a] of a large company the relative investment of the whole system was for generating plant 32.5%; for transmission 9%; for substation 12.5%; for local distribution 26 %; and for miscellaneous 20%. In this case the three elements of the distribution system constituted nearly 50% of the total investment and the local distribution system more than half of this.

[c] The losses in the distribution system are very great, of the order of 15-20 per cent of total energy generated, and they have to be transmitted through the rest of the system. Therefore, it is evident that the distribution system must be laid out very carefully with a view of economy, but despite this fact the distribution system is probably the most neglected part of the electric system as regards economic design. This may be due to the great multiplicity of problems such as determining the most economic size of conductor, voltage, span, route, etc; transformer ratings and space; substation locations, etc. And all these factors are interdependent and are in many cases governed by considerations other than purely economical ones. Another reason is the great uncertainty of load conditions, of load growth, etc. A third reason is that good service must be considered first of all so that the ideal is to distribute the generated energy at the least possible

a) 41-p.35 b) 37-p.107 c) 37-p.108

cost consistent with good service.

The requirements of satisfactory service[a] are:

I) Dependability; 2) Constant or nearly constant voltage; 3) Balanced voltage(if polyphase); 4) constant frequency and freedom from inductive interference with telephone lines; 4) good power factor; 5) and service at minimum cost.

Elements of the distribution system and distribution practice .

Substations[b] are used for the following purposes:

a. To receive alternating-current from high voltage transmission feeders and lower the voltage for local distribution.

b. To convert alternating-current into direct-current for local distribution.

c. To convert alternating-current received from feeders at 25 cycles to 60 cycles for local distribution.

d. To convert alternating-current from constant potential sources to constnat current, either direct or alternating, for the supply of lighting circuits.

e. To house storage batteries used as load regulators or reserves on direct-current systems.

f. To house feeder regulators for the control of voltage on lighting circuits.

Conversion to direct-current may be accomplished either by motor-generator sets, by synchronous converters, or by mercury-arc rectifiers. Motor-generator sets are more expensive and less efficient than converter equipment, but occupy less space, are better adapted for power-factor correction and are more reliable in operation. [c] "The saving in floor space occupied by a motor-generator set over that occupied by a synchronous converter and its accessories has heretofore been advanced as an argument in favor of the former, but as the induction regulator and series booster are no longer necessary, this advantage of the motor-gen-

a) 32 - p.5 b) 16 - p.374 c) 52 - p.1071

erator set is partially overcome. If the transformers belonging to a synchronous converter set can be located on a gallery, a greater capacity in synchronous converters than in motor-generator sets can be installed in a substation of given floor space."

The large mercury-arc rectifiers have been used mainly for railroad electrification, but they are equally well adaptable for lighting service. On account of absence of mechanical inertia and commutators they are the type of apparatus which is the least sensitive to sudden load peaks. Another valuable characteristic is that energy cannot flow from the direct-current to the alternating-current network. This fact is of considerable importance because a satisfactory parallel operation of rectifiers connected to two independent networks is thereby possible. The two networks are not restricted in that they must have the same frequency, nor does a change in the frequency affect safe operation as it does in the case of synchronous converters connected to two independent networks.

In Germany a distribution substation[a)] was enlarged with rectifiers and the reasons for using this apparatus were the following:

1) About equally high efficiency of rectifiers for all loads.
2) Noiseless, 3) quiet and simple start up, 4) little attention,
5) practically no wear, 6) light weight, therefore no special foundations, 7) high capacity for overload, 8) simple and cheap reserve,
9) easy repair.

The efficiency of a rectifier increases with the voltage and as most distribution systems have a rather low voltage, the rectifier does not show up to such a great advantage as it does in railway service with high voltages.

<u>The economic size and spacing of substations</u> involve a proper balance between two classes of costs, substation and transmission cost on the one hand and primary feeder cost on the other.[b)] The method is to

a) 56 - p.414 b) 71 - p.1200

trical set is especially obvious. If the transformer [illegible] a synchronous converter [illegible] be located in a railway, [illegible] formerly in synchronous converters [illegible] mercury-arc rectifiers [illegible] installed in a substation of [illegible] stage.

The mercury-arc rectifiers were [illegible] used mainly for railroad electrification, but they are equally well adaptable for lighting service. On account of absence of mechanical inertia and commutator, they are the type of equipment which is the least sensitive to sudden load changes. Another valuable characteristic is that energy cannot be fed from direct-current to the alternating-current system. This fact is of considerable importance because [illegible] parallel operation of rectifiers connected to the independent networks is [illegible] possible. The two networks did not [illegible] that [illegible] the same frequency, nor does a change in the frequency affect each [illegible] as it does in the case of synchronous converters [illegible] two independent networks.

In Germany a [illegible] substation [illegible] with rectifiers, and the reasons for using this equipment were the following:

1) About equally high efficiency of rectifiers for all loads, 2) Noiseless, 3) quiet and simple [illegible], 4) light [illegible], 5) practically no [illegible] weight, therefore no special foundations, 7) high capacity for overload, 8) simple and cheap control, 9) easy repair.

The efficiency of a rectifier [illegible] most distribution systems [illegible] does not [illegible] as it does in railway [illegible].

The economic size and spacing of substations. [illegible] between the [illegible] the two [illegible]

make different layouts and compute annual charges for all of them, put the result in graphical form and keep as close to the minimum cost as possible. The most strictly economical arrangement is not always obtainable, because many other factors must be considered in each particular case, such as existing duct lines, cost of land, load center of area to be fed, relations to other substations, which factors are influenced by local conditions. But fortunately, the above mentioned graph is very flat so that even a considerable deviation from the most economical scheme does not materially affect the total annual charges.

Some idea about the most economical size of substations may be had from the following table which has been calculated [a)] for a two phase, 3 wire, 2300 volt system:

Load ⟶ Density		Most Economical substation
1500 KW/	square mile	20 000 K W
3000	"	24 000 "
4500	"	28 000 "

As the load is constantly growing the substation should be designed with this in view and the problem is therefore to select a size which may be adopted as a general standard and yet be most economical for average conditions.

The direct-current substation seems to be a thing of the past because in modern systems of distribution it is not needed. In large metropolitan areas it becomes exceedingly difficult to find proper places for substations and ~~the cost of~~ land is very expensive; this may be the deciding factor as to why the tendency is towards abandoning the direct-current system and go over to an alternating-current network.

Primary feeders. As mentioned above the economic size and length of primary feeders depend upon the economic size and spacing of substations as well as the economic size of feeder copper.

a) 71 - p. 1200

The latter is a problem of balancing fixed charges on the copper against line losses. When the economic size and spacing of substations have been found this also determines the length of the primary feeder, but good voltage regulations may limit length of a feeder below the economic limit.

The average length of primary feeders is from one to ten miles and the predominant system (used on 45% of all systems in this country) is 3 phase 4 wire star 2300/4000 volts; next (23%) comes 3 phase delta 2300 volts, then (6.6%) 2300 volts single-phase and 2300 volts two-phase (4.6%). The voltages vary from 2200 to 13 200 volts depending on type of territory served, that is, low voltage is used for dense loads, high voltage for outlying districts. In New Orleans the adoption of the latter high voltage permitted the elimination of substations, the feeders coming directly from the generating station.[b]

The relative amounts of copper required in various distribution systems are as follows:[a]

Type of system	Comparison based on minimum potential between wires	Comparison based on maximum potential between wires
Single-phase, 2 wire	100 per cent	100 per cent
Single-phase, 3 wire	37.5	----
Two- phase, 3 wire	72	144
Two-phase, 4 wire	31.4	-----
Two - phase, 5 wire	31.25	-----
Three-phase, 3 wire	75.0	75.0
Three-phase, 4 wire	29.17	100

<u>Transformers:</u> [a]The economic spacing of the transformers is closely related to a study of economic length of secondaries. The size of the transformers depends upon the spacing because a given load density requires a definite transformer capacity, divided into a number of

a) 71A-p.732 b) 74A-p.856

smaller transformers. It is desirable to use as large transformer units as possible because then their cost per KVA and the losses will be lower. However, by increasing the size and spacing of the transformers the cost of and the line losses in the secondaries will increase, ~~and~~ the problem is therefore to secure an economic balance between the cost of the secondaries and their losses.

The spacing of the transformers is also much influenced by the street layout. The spacing varies from I35 feet to 3000 feet, the average being I000 feet.[a] The size of the transformers must be taken larger than required at the moment in order to take care of load growth, but this should be practiced conservatively as the cost of change is not high, provided the transformer vault is made large enough.

The practice of connecting the transformer leads varies greatly, the same company often using different connections. Therefore in the list below the sum of the percentages add up to more than I00.

The first list[a] gives the transformer connections for power service alone, the second for combined power and light.

Power service	Per cent of companies using each type of system
Closed delta, 3 wire	85
Open delta, 3 wire	39
Star, 4 wire	IO
Combined power and light	
Closed delta, 4 wire	7I
Open delta, 4 wire	39

<u>Secondary system</u>. The economic length of the secondaries is determined in connection with the transformer spacing. The length varies from 300 feet to 2500 feet.[a] The bulk of the secondary system in residential districts is single-phase, 3 wire, but there is no consistent practice by any one company the reason being that the load density varies and the type of load is different, that is, whether the service required is for light alone or for combined light and power.

[a] 71A - p. 732

Some companies use different types of systems. Therefore in the table below the percentages add up to more than I00.

Secondary system				Per cent of companies using each type of system
II0 volts,	2	wire,	direct-current	20
II0 "	3	"	direct-current	45
II5 "	3	"	direct-current	35
220 "	[illegible]	"	single-phase	47
220 "			three-phase	33
230 "			single-phase	3I
230 "			three-phase	27
460 "			three-phase	I4

COST COMPARISON OF DISTRIBUTION SYSTEMS

The cost of supplying a distribution area of one square mile with a certain load characteristic is examined below.[a)] The area has a sustained peak load of I2 000 KW at 230 volts, with an annual consumption of 46 000 000 Kwhrs corresponding to a load-factor of 0.44.

Three schemes are considered:

I) The Edison direct-current system using one substation at load center.

2) The same system using four substations.

3) The three-phase, four wire alternating-current system with a bank of transformers at each street intersection, supplied from a single substation at 2300 volts. Power factor 0.83.

For all three cases the amount of copper required and the losses in the low-tension mains are practically the same. The table below compares the amount of copper required in the feeders and the losses in same.

System	I	2	3
Number of substations	I	4	I
Number of feeders	64	64	I0
Average length, miles	0.50	0.25	0.42
Maximum length, miles	0.87	0.37	0.62
Weight of copper, tons	560	280	94
Annual feeder losses in millions of Kwhrs	6.4	3.2	I.6
Annual feeder losses, in per cent	I4.0	7.0	3.5

The following average costs are assumed:

Generating station	$I40	per kilowatt
Series arc substations	I00	" "
Direct-current substations	70	" "
Alternating-current substations	40	" "

To find the investment cost per kilowatt delivered at the substation bus or at the customer's services one should add the cost of the transmission and, respectively, the cost of the distribution system including substations or of the distribution transformers.

a) 72 - p. 379

Thus the following investment costs per kilowatt are found:

Point of delivery	Substation bus	Customer's service
The series system	$633	$666
The direct-current system	356	407
The low-tension alternating-current system	298	347

Similarly, the operating costs based on the year 1920 were found to be in cents per Kwhr as below. These costs include cost of fuel, attendance, maintenance of stations and lines, but do not include fixed charges on investment. The following efficiencies were assumed and included:-

Series substations	74.8 per cent
Direct-current substations	81.4 " "
Alternating-current substations	98.0 " "

Operating costs in cents per kilowatt hour:-

Point of delivery	Substation bus	Customer's services
The series system	1.96	2.07
The direct-current system	1.57	1.78
The low-tension alternating-current system	1.28	1.49

Conclusion. The low-tension alternating-current system is much cheaper both in first cost and in operation than the direct-current system.

Some other points must, however, be remembered. The conditions of delivery into a densely loaded district favor the direct-current system, first, because it is difficult to find transformer vaults in the streets for the alternating-current system, second, because the protection of the storage battery reserve on the direct-current system is of great value, and where there are many elevators, printing presses and other variable-speed machines the direct-current motors are better adaptable to fine regulation. However, a very important point

point is that in congested city areas it is extremely difficult to obtain land at reasonable prices for the direct-current substations, and as most transformers for the alternating-current system can be mounted directly in the customer's buildings the problem of space for the latter is practically eliminated. Furthermore, this latter arrangement gives very good regulation also in the top stories of very high buildings, because transformers can be mounted on each floor. A similar arrangement would not be practicable for the direct-current system.

To obtain maximum output from all plant equipment per dollar invested there should be used only one type of generating equipment and one distribution system in order to take advantage of diversity of loads and to obtain the high load factors possible through the use of interconnected generating stations carrying diversified loads. This idea can most nearly be obtained with alternating-current systems.

General Comparison of distribution systems.[a)]

Distribution systems may be classified as to the nature of the current used - direct-current or alternating-current; as to method of connection - either series or parallel connection; and further as to number of phases, of conductors and as to voltage and frequency.

In the historical development of the distribution system several types of systems have been used as follows:

1) The series system. All equipment is connected in series, constant value of current is used, and the voltage varies with the load. It is limited almost entirely to street lighting where all devices are in use at the same time. Alternating-current can be used, but direct-current was most common before the advent of the incandescent lamp.

2) The two-wire parallel systems. All loads are connected in parallel, the voltage is held constant and the current varies with the load. Direct-current applied to this system and the following one has limitations, because of small radius of distribution, and because of the great number

a) 72-p.379

of substations requiring rotating machinery for transforming energy from alternating-current to direct-current. These substations are more expensive both in first cost and in operation than alternating-current substations and their economic size ~~of them~~ is much smaller than it is now common practice to have.

Alternating-current applied to this system in the form of single-phase current has the advantage of a mimimum number of conductors and hence the minimum first cost for distributing mains. This system is used very generally for lighting circuits, but applied to motors it is in general limited to units of 10 horsepower because single-phase motors cost more than polyphase motors and produce more disturbance in starting. Also the feeders require 33 per cent more copper than equivalent three-phase feeders.

3. The three-wire direct-current system, also called the three-wire Edison system, is widely used in metropolitan areas. The double voltage can be used as compared with the two-wire system.

4) The three-phase three-wire parallel system is very commonly used since it is readily derived from a three-phase primary distribution and transmission system and is well suited for motor applications; The double voltage can be used as compared with 2) and it requires only 75 per cent as much copper as an equivalent single-phase system.

5) The three-phase, four wire system is used much for primary distribution at 3800 volts between phases and 2200 volts between any phase and neutral. The advantage of 3800 volts distribution is that the radius of distribution is about ~~the~~ double that of 2200 volt.

6) The two-phase and four-phase systems. The latter is really a superposition of 2 two-phase systems. The two-phase system may be either three-wire, four wire, or five wire. The three-wire system is as economical in regard to copper as the three-wire, three-phase system, but the voltage regulation is somewhat difficult without phase compensators.

The four-wire system is substantially the same as the single-phase system except that two-phase motors can be used. The five-wire system gives very satisfactory service and the first cost is low. A great advantage of two-phase systems is that only two transformers are required to supply polyphase energy to motors.

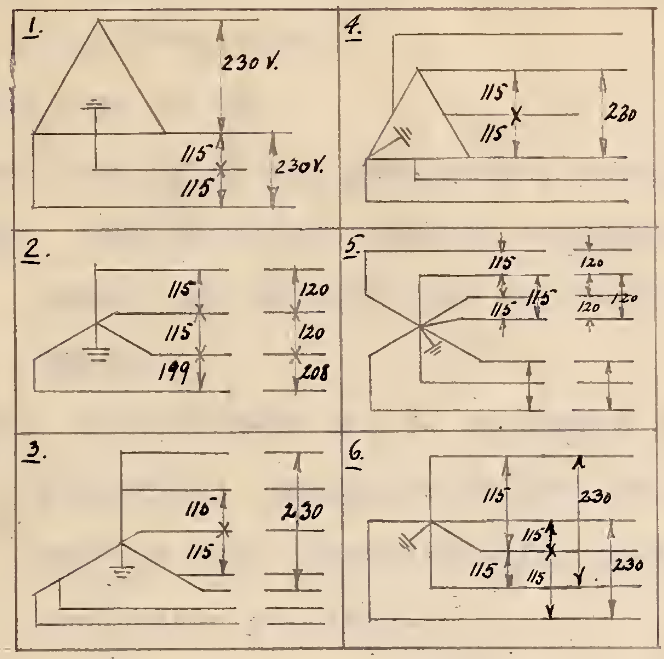
Technical comparison of polyphase secondary systems.

It is very difficult to design a satisfactory distribution system partly because it must comply with the present standard for motors and lamps. The standard motor voltage is 220 and the lamp voltage is I20 on most systems already installed. Unfortunately these standards are not easily adaptable to three-phase distribution where one either gets I20-208 volts, or II5-230 volts, or II5-I99 volts. When a 220 volt motor runs at low voltage it may heat unduly and even 208 volts is too low although several reports indicate satisfactory operation at this voltage, perhaps because the motors were rated too high.[a] Anyway, there is a reduction in rating of motors when they run on low voltage and the cost per horsepower load is increased about IO per cent with standard design. Furthermore, much more careful voltage regulation must be maintained with the lower voltage than with 220 volts. Of course, 220 volts can be supplied from I00 or 208 volts by using autotransformers for each motor, but this is an undesirable and uneconomical arrangement.

Lamps rated at I20 volts can operate satisfactorily on II5 volts, although with a loss in brightness but at the same time a longer life.

The diagrams below[a] show the most practicable secondary connection schemes for combined light and power service and the advantages and disadvantages of the respective schemes are listed below. Figures I-5 show different three-phase systems, figure 6 is the two-phase, five-wire system.

a) 47- p1316



I) Advantages: II5 volts for lamps and 230 volts for motors

Disadvantages: Unequal voltage to ground, all lighting load on one phase, unbalanced voltage, and unequal sized conductor.

2) Advantages: Load balanced on three phases, voltage to ground balanced and II5 or I20 volts for lamps.

Disadvantages: I99 or 208 volts for motors. Two single-phase meters or one polyphase meter is required for metering on single-phase three-wire service, whereas the ordinary single-phase, three-wire system only requires one single-phase meter.

3) Advantages: Load balanced on three phases, voltage to ground balanced, II5 volts for lamps and 230 volts for motors.

Disadvantages: Seven conductors; special transformers with taps; it is

difficult to design a line of transformers with these voltages so that the different sizes will operate satisfactorily in multiple with other sizes and other types.

4) Advantages: Load balanced; II5 volts for lamps and 230 volts for motors.

Disadvantages: Six conductors and voltage to ground unbalanced and too high (230 volts).

5) Advantages: Same as #2.

Disadvantages: Same as #2 and furthermore requires seven conductors.

6) Advantages: Load balanced; voltage to ground balanced; II5 volts for lamps; two transformers per bank and transformers standard ratio.

Disadvantages: Transformers are T- connected if fed from three-phase primaries; polyphase motors are two-phase which do not have as good characteristics as three-phase motors. Five conductors required.

REQUIREMENTS FOR DISTRIBUTIONS SYSTEMS

"The ideal system for general distribution of lighting voltage must ~~be~~ comply with several requirements:[a]

I) It must be polyphase so as to permit an economic operation of motors. 2) It must be a symmetrical polyphase system so that the line drop due to a balanced load will not cause distortion of the voltage either in magnitute or phase, and the unbalance in voltage caused by unbalanced loads must be small. 3) The voltages available must be suitable for both light and power requirements and must not exceed a fairly safe maximum. 4) The energy delivered to both light and power load must be capable of being measured by a single meter. 5) The investment cost per KVA delivered must be low. 6) Efficiency high. 7) Number of conductors as small as possible. 8) One conductor must be a neutral which can be grounded in such a way as to limit the voltage of all other conductors to ground to a value below I50 volts and which preferably is symmetrical in voltage relations to the other. 9) This system must be capable of simple and economical derivation from the primary distribution system and this in turn from the transmission system.

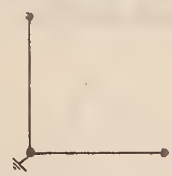
The only polyphase systems which can be considered are the ones listed on the following pages."

CONCLUSION :: " The three-phase four-wire system seems to fill most satisfactorily all of the requirements and compares favorably with the direct-current three-wire system, the one drawback being its adaptation to the present normal voltages of lighting and power apparatus as shown in the table.

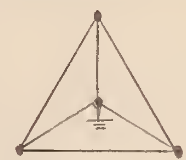
The same system was also found satisfactory for primary distribution and therefore the only logical course seems to be the general adoption of this system. From the point of safety to life and from fire this system is the one that comes nearest to the direct-current system where there is practically no danger to life with the low voltage used.

a) 72-p. 379

COMPARISON OF SYSTEMS FOR SECONDARY DISTRIBUTION

		Two-Phase Three-Wire 115 or 230 Volts	Two-Phase Four-Wire 115 or 230 Volts	Two-Phase Five-Wire 115 or 230 Volts
System				
Symmetry		N.G.	O.K.	O.K.
Voltage		115 volts too low for power- 230 volts too high for light	115 volts too low for power- 230 volts too high for light	O.K.
Metering		O.K.	O.K.	O.K.
Relative Investment	115 volts 230 "	1.660 1.830	1.566 0.783	0.978
Relative Losses	115 volts 230 "	1.476 0.738	2.090 1.045	1.045
Number of Wires		3	4	5
Grounding		O.K.	N.G.	O.K.
Transformation		6.7% lost capacity	6.7% lost capacity	6.7% lost capacity

COMPARISON OF SYSTEMS FOR SECONDARY DISTRIBUTION

		Three-Phase Three-Wire 115 or 230 Volts	Three-Phase Four-Wire Symmetrical	Direct Current or Single-Phase Three-Wire 115 or 230 Volts
System				
Symmetry		O.K.	O.K.	O.K.
Voltage		115 volts too low for power- 230 volts too high for light	120 volts slightly high for light- 208 volts slightly low for power	O.K.
Metering		O.K.	O.K.	O.K.
Relative Investment	115 volts 230 "	1.358 0.679	1.000	1.174
Relative Losses	115 volts 230 "	1.808 0.904	1.000	1.045
Number of wires		3	4	3
Grounding		N.G.	O.K.	O.K.
Transformation		O.K.	O.K.	Complex

The three-phase system is also very flexible because it can be extended into new territory as a single-phase system for light loads using a two wire circuit and can later be supplemented by the addition of two wires so as to take care of increased load as the territory is developed. The system can take care of any type of load thus allowing it to enjoy all of the advantages of diversity factor which is essential for the most economical operation of central station service."

ALTERNATING-CURRENT LOW VOLTAGE NETWORKS

"Any installation should be called a network where transformers at various locations have their secondaries tied together."[a)]

The most important problem in modern distribution practice has been the development of such a system which could be used with both power and lighting services on the same mains in areas of high load density and which would approach in reliability the Edison direct-current system, used commonly in congested metropolitan areas. The reliability of this latter system is very remarkable. There are areas in which the service has not failed a moment in thirty years or more. This reliability is due largely to heavy conductors fed by numerous units all supporting each other. Minor faults can be burned off and cleared without interrupting service. The Edison system is still favored in many places for high speed elevators, printing presses and similar service, where fine speed regulation is required, but there is a general tendency to favor alternating-current also for such purposes, because it is claimed that equally satisfactory service can be given on alternating-current, that the motors are cheaper, have better efficiency and lower maintenance cost and better acceleration. To sum up "[b)] the disadvantage found in variable-speed motor applications are compensated for, to a large extent, by the extremely simple constant speed motors. The common problem in considering the possibility of combining light and power on one set of mains and services is the permissible variation in illumination of incandescent lamps, due to change in voltage. The principle cause of voltage variation is the starting current required by motors. Two per cent instantaneous variation in voltage cannot be detected and three per cent is the maximum possible for the highest grade of service."

a) 72A-p.981 b) 73-p.844

Alternating-current distribution has been in general use for many years on overhead lines for isolated and widely scattered loads because of its economy in first cost and low operating expenses. Underground alternating-current systems have been in use in a number of places for several years, but the adoption of networks is of recent date except in one case, the United Electric Light and Power Company of New York City, which has been using networks since the beginning of this century.

During the past two or three years thirty cities have adopted this new system and always with great success.

The main consideration in the adoption of networks is the question of reliability, because reliability is of paramount importance in metropolitan distribution systems. But during the last few years very important developments have been made in the adoption of this type of alternating-current distribution and it is now claimed that it is possible to provide satisfactory alternating-current service of a very high degree of reliability on account of the multiple feeds obtainable to all parts of the network.

The low-voltage metwork should be so designed that it "eliminates its own faults."[a] That is, the conductor sections should be so small that a fault burns them over, or at least the heat produced when a short circuit occurs should develop heat enough to cause an arc fault to occur. It is then possible by means of a motor-operated protector to make the system protect itself against any fault which may happen.

The future distribution system will then probably be characterized by the following features: a low voltage three-phase, four wire alternating-current underground network; underground multiple-transformer vaults; the elimination of the substations by using a sufficiently high voltage for primary distribution; unit generators in the central stations eliminating the high voltage bus in the station; synchronizing "at the load", that is through the network.

a) 73 - p.844

alternating-current distribution has been in general use for the many years to overhead lines for isolated and thinly scattered loads, because of its economy in first cost and low operating expenses. Three-phase alternating-current systems have been in use in a number of places for several years, but the adoption of networks is of recent date except in one case, the United Electric Light and Power Company of New York City, which has been using networks since the beginning of this century.

During the past two or three years fairly cities have adopted this new system and always with great success.

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The low-voltage network should be so designed that it "clears" its own faults. That is, the conductor sections should be so small that a fault burns them open, or at least the heat produced when a short circuit occurs should develop heat enough to cause the fault to clear. It is thus possible by means of a secondary network protection to make the system protect itself against any fault which may happen.

The future distribution system will thus probably be characterized by the following features: a low voltage three-phase, four wire alternating-current underground network; underground substations transformer vaults; the elimination of the substations by using a relatively high voltage for primary distribution; unit substations in the network stations eliminating the high voltage bus in the station; synchronizing "at the load", that is through the network.

This gives the following advantages:[a) no large concentrations of energy in the generating stations and the attendant difficulty of providing circuit breaker protection; no problem of tie cables, the only tie between generating stations being the network which appears to be unlikely to transmit disturbances from one generator to another; no problem of load control or of wattless current control between the different generating stations; system stability ~~is~~ a maximum; and the service ~~is the~~ most economical.

a) 73A - p.515

THE CONVERSION OF DIRECT-CURRENT SYSTEMS TO ALTERNATING-CURRENT NETWORKS

It is quite generally agreed that the direct-current service should be limited to its present extent, and in some cases, gradually supplemented by alternating-current, since the latter system is claimed to be more economical and more easily adaptable to increases in load.

Therefore, the adoption of alternating-current distribution also for metropolitan areas has been due in most cases to the desirability of limiting the growth of the direct-current systems in those areas. Only in a very few cases has it been found economical to completely displace the direct-current system, but in general this system will still be maintained either in separate districts or on parallel lines, the alternating current system being preferred for large new customers so that large individual blocks of alternating-current loads are superimposed on the old distribution system. There are some advantages in having both systems in use, f. ex. for emergency light service for theaters, in automatic telephone exchanges and also because certain customers prefer the direct-current even if they shall pay a higher rate. But it is clearly advantageous to have ~~also~~ alternating-current supply also in all districts, f.ex. for X-ray machines and other power requirements where alternating-current is most satisfactory and economical to the consumer.

a) "Any scheme involving a complete change-over on large direct-current distribution systems in the industrial and business areas of large cities would undoubtedly be prohibitive. A change must come gradually by supplying large additional power or lighting consumers from the high-tension alternating-current mains by means of transformers installed on consumers' premises."

"There are various methods whereby a change-over may be accomplished viz: I) Laying an additional single-core cable alongside each existing distributor to make a three-phase four-wire system.

a) 69- p.791

This method has little to recommend it as the advantages to be gained would be outweighed by the heavy expense that would be incurred in opening and reinstating roads.

2) Replacing existing mains with four-core cables. The use of this method will depend to a considerable extent on the condition of the mains and whether the increasing demand will warrant the heavy expenditure.

3) Using the two outer and the midwire for two phases and the neu-tral of a three-phase system. The cost of such a change-over is comparatively small and can be quickly made, as consumer's services do not require alteration in any way. The direct-current meters must of course be changed.

Unfortunately, the disadvantage of this arrangement is that the section of the neutral conductor governs the current-carrying capacity of the outers as the current in the neutral is more than out-of-balance current.

4) Using single phase, three-wire transformers. This is probably the most economical method of dealing with a change-over. By cutting the network into sections existing distributors will be capable of dealing with a much larger load owing to their being shorter and the voltage drops less.

By this last method there are two arrangements open:

a) One transformer installation with three single-phase, three-wire transformers each connected across different phases of the high-tension mains; each transformer to supply a separate area, the load of which should be arranged to be as nearly equal as possible; short feeders to be run from each low-tension panel to the centers of gravity of each area.

b) Three separate transformer vaults, each one of which should be placed as near as possible to the centers of gravity of three separate areas. The high-tension main to be looped into each transformer and the sin-

gle-phase, three-wire transformers balanced across different phases; distributors to be connected straight on to the low-tension distribution panel."

ECONOMICS OF CHANGE-OVER

[a] " Kansas City, Mo., like many of the older cities of the United States, still retains direct-current service for light and power in the congested retail business district - the so-called Edison district. A few years ago the company desired to narrow its Edison district to the minimum, thus leaving only the dense business district to be served by underground direct-current mains. This necessitated the changing of 2000 or more power and lighting services from direct-current to alternating-current.

Having determined upon the change, the problem presented was: Upon what basis should the customer's services be changed: I) Customer to stand entire equipment expense; 2) Company to stand entire equipment expense; 3) Company and customer each to bear a proportionate share of equipment expenses.- Good will and equity prevented the first plan from being carried out. The second plan was rejected because of the heavy expense to the company. The plan determined upon was based upon charging the customer the accrued depreciation upon his equipment, the company to bear all expenses incident to the change, including wiring and all new motors, fans, etc. A fair average depreciation of 5 per cent per year was decided upon. From an accounting standpoint it meant simply that a customer with equipment originally costing $I,000 and ten years old had at the time of the change a motor worth $500 and also had $500 in his depreciation reserve account. The company therefore proposed to remove his $500 equipment, install new equipment worth, say, $I,000 and take the customer's $500 depreciation reserve- the net transaction being a matter of accounting for the customer. The plan has been received favorably."

a) 68- p. 1265

The Brooklyn Edison Company carried into effect a few years ago, a plan of change-over in order to make the overloaded direct-current system comfortable and safe. Instead of reinforcing the existing inefficient direct-current system by adding feeders and mains and building additional direct-current substations at tremendous cost the method adopted to relieve the direct-current system was to change over a sufficient amount of load to the alternating-current system at a point where this could be done most economically and with the least inconvenience to consumers. "It was frankly recognized that with the art as then developed, short-time interruptions were more likely to occur on an alternating-current system than on a direct-current system but it was felt that with the development of a closed low-tension network an alternating-current system would be substantially better than anything that could be developed with direct-current. An interesting result of these changes has been the increase in overall system efficiency from a fairly steady value of 78 per cent during the preceeding years to 82 per cent at the present time. This will continue to increase as a greater portion of the total load is taken on the alternating-current system."[a)]

In connection with this policy of change-over certain changes took place in other parts of the distribution system. These changes may be summarized as follows:"[a)] The primary distribution system has been changed from 2400 volts, two-phase to 2400/4150 volts, three-phase, which increased by 50 per cent the amount of power that could be transmitted over existing distribution feeders and at the same time reduced the losses by 25 per cent. In the substations it was found that with the same buildings, by taking out certain unnecessary parts of the switching equipment, two-phase stations could be converted into three-phase stations of 50 per cent greater capacity with the addition of only a fraction of the equipment normally needed for this extra capacity."

[b)]In Seattle "a study was made of the relative efficiencies and comparative economies of the direct-current and the alternating-current

a) 58-p.38 b) 72-p.1375

systems of distribution for supplying the same load at consumer's premises. In general it was found that under conditions obtaining in the Seattle system the losses in substation transformation and the distribution system were of the order of 6-8 per cent of substation input with the alternating-current system, as compared with 20-25 per cent with direct-current distribution. An analysis was made of the comparative net earnings obtainable by serving the same total load and area with alternating-current for the principal service as compared with direct-current series. It was found that an increase on the order of IO per cent of the gross revenues may be looked for owing to the higher efficiencies and lower costs applying to alternating-current service. These conclusions and figures do not necessarily apply to any other systems or conditions but seem to indicate a decided economy in favor of alternating-current service."

A STUDY OF CHANGE-OVER

General In New Orleans[a] there are at present two 120/240 volts direct-current three-wire Edison systems which parallel each other. They are partly overhead and partly underground. The two systems cover two sections with widely different load densities. These two sections will be called A and B. One of the sections, (Section B), comprising the old French quarter, is also served by an alternating-current system, the 4000 volts four-wire grounded neutral, radial system.

The Edison systems had established an excellent record of service, particularly for the high load density in the business center, Section A. This system had proved extremely reliable for this heavy service, backed up, as it generally is, with large storage battery reserves and ~~up~~ until very lately it was the only system which could give satisfactory service for high-speed elevators. However, modern alternating-current equipment can now meet satisfactorily all the special requirements of metropolitan business centers and when it became necessary to completely rehabilitate the underground distribution system in New Orleans it was decided to make a thorough study of the present direct-current system and of different alternating-current systems for the purpose of determining how the rehabilitation should be made and what the future policies should be.

Method of approach A gradual replacement of the existing direct-current system with an alternating-current system was considered and a period of thirty years was assumed before the new system would completely replace the old system.

The calculations cover the first ten years of this period and the equipment is based on a load equivalent to the total load growth of the ten years period in the underground district plus one third of the existing direct-current load in section A and all the existing direct-cur-

a) 74A - p. 856

rent load in Section B.

To determine the load growth sufficient data were not available because the exact boundaries served by the two direct-current systems were not recorded for past years. Therefore, the data on the yearly peaks of the generating stations were given particular weight in estimating future growth.

The future investment was estimated from actual layouts of the future systems and actual prices were used. Substation~~s~~ estimates were based on data covering existing stations.

To determine the power factor and transformer demand factors data were used from other systems.

The losses were calculated ~~based~~ for an assumed ~~certain~~ layout based on a study of the economics of transformer spacing and sizes of secondary mains.

a) "The future energy charge is a very difficult problem to approach, because an exceedingly large number of possibilities can be imagined. The following points were observed:

I) Subdivision of unit cost into a demand charge and a kilowatthour charge.

2) Subdivision of the demand charge between the various classes of apparatus through which the losses pass.

3) In-clusion in the demand charge of a charge for wattless kilovolt-amperes produced by the alternating-current distribution apparatus."

<u>Types of systems considered.</u> b) " Five types of distribution systems were included in the study and these may be briefly described as follows:

I) <u>I3 200 volts primary with network secondary.</u>

In this sytem as in all the other alternating-current systems considered, the service was assumed to be three-phase, four-wire II5/200 volts. This is the system which shows the greatest economy of all those considered and which was selected for New Orleans.

a) 74A-p.866   b) 74A-p.858

2. I3 200 volts radial.

This system differs from the first in that each transformer bank feeds an isolated section of secondary mains and no attempt is made to operate the transformers in parallel.

3. 4 000 volts primary with network secondary.

In this case the usual step-down transformer substation is necessary to convert from I3 200 volts to 4 000 volts.

4. 4 000 volts radial,

Each 4 000 volts feeder serves an individual district and each distribution transformer bank serves an isolated section of secondary mains.

5. Combined direct-current and alternating-current.

In the first four cases the gradual elimination of the direct-current system was contemplated. In this case the presence of an existing direct-current distribution system eliminated a large item of investment tending to favor the economics of direct-current service."

Conditions of change-over.[a] "Certain difficulties will be encountered in the change-over. One is the difficulty of obtaining space underneath the streets for the location of transformer manholes. As far as possible the transformers will be located in vaults on the customer's premises which method has the good features of reducing the cost and of placing the transformers near the load to be served.

Existing lighting services can be transferred directly from the direct-current system to the new alternating-current mains. Existing direct-current services which involve large amounts of motor load need not be transferred to alternating-current at once. It is intended to gradually reduce this type of load and ultimately eliminate it by extending the process over a period of years sufficient to allow for I00 per cent depreciation of existing equipment as far as possible.

a) 74A - p.862

A certain amount of actual change-over of customer's equipment will, of course, be desirable from time to time, and the expense of doing this must be borne by the company."

Tabulated summary of results

"The figures for total investment, overall efficiencies, etc.,include all of the distribution system between generating station feeder circuit breakers and the point of connection of the service laterals to secondary mains. The service laterals and service equipment were not included in the calculations, since these in general would be the same for all five systems except for certain differences in the cost of meters,etc., between alternating-current and direct-current service and these differencies would be in favor of the alternating-current systems.

It should be noted particularly that throughout the calculations the investment figures were intentionally made more liberal for the novel systems, thus placing a handicap on these systems.

The investment figures for the direct-current system include what might properly be called renewals and replacements for the present system, but which for convenience have been combined with the investment in new equipment to obtain the investment totals shown in the tables."

Below is given the total new investment for the various systems.

System 1 Network I3 200 v.	2 Radial I3 200 v.	3 Network 4000 v.	4 Radial 4000 v.	5 Combined A.C. and D.C.
$I,378,700	$I,666,300	$I,982,300	$2,I89,600	$2,394,800

Thus it is seen that the saving in dollars and per cent of total investment for system I is as listed.

	$	Per Cent
System I versus 5	I,0I6,I00	74
System 2 versus 3	603,600	44
System 2 versus 4	523,300	38
System I versus 2	287,600	2I
System 3 versus 4	207,300	I5

The overall annual efficiencies for the different systems are:

System	I	2	3	4	5
Efficiency	94.7	93.7	90.0	89.3	76.5

The summary below gives the total annual charges:

System	I	2	3	4	5
Charges on new investment at I4%	$I93,000	$233,000	$277,500	$306,500	$335,300
Energy charges for losses	I8,920	22,730	37,680	40,440	I03,206
Demand charges for losses	32,3I0	27,490	6I,I70	52,050	I23,980
Substation operators salaries	------	------	II,900	II,900	Automatic
Maintenance of network switches	I,780	-------	2,500	------	-------
Total annual charges	$246,0I0	$283,220	$390,8I0	$4I0,890	$562,486

The savings in total annual charges in dollars and per cent of total for network, I3 200 volts, are as follows:

	$	Per Cent
System I versus 5	3I6,476	I28
System I versus 3	I44,800	59
System 2 versus 4	I27,670	52
System I versus 2	37,2I0	I5
System 3 versus 4	20,080	8

Conclusion. The data presented above gives sufficient justification for introducing a certain new type of alternating-current system paralleling the present underground direct-current system in New Orleans. Both as to total investment and operating charges the new system shows considerable saving during a ten-year period of growth.

The new system selected is characterized by the following features:

I) The distribution substation is eliminated by choosing a primary distribution voltage of I3 200, the distribution transformers being fed directly from the generating station by feeders, each of which is controlled by automatic induction regulators located in the generating station. Thus an important saving is effected by the elimination of primary protective devices. The transformer capacities are reduced by taking advantage of the diversity factor in the secondary network.

2) This network consists of interconnected low-voltage alternating-current, three-phase, four-wire 115/200 volts mains served by a comparatively large number of distribution transformers. Only one protective device is used in the network, namely a reverse-energy opening switch with automatic reclosing features.

[a] "The reliability of this system is practically equivalent to that of the substation itself. The simplicity of the system constitutes a reasonable amount of insurance against failures. That is, the fact that multiplicity of apparatus such as substation rotating apparatus, transformers, numerous circuit-breakers, etc., is avoided should greatly reduce the number of apparatus failures. Full reliance is placed on no one switch and a failure of one or more switches will not necessarily mean service interruptions over a large area because the faulty section is eliminated.

Thus, special consideration has been given to reliability of service and the selected system contains features which provide a high degree of reliability, comparable to that of the best modern direct-current systems, if stand-by storage battery equipment be eliminated from consideration."

a) 74A-p.866

TRENDS OF DISTRIBUTION PRACTICE IN GREAT BRITAIN

The general tendency of distribution in Great Britain runs somewhat parallel to the tendency in the United States as reviewed at some length in the preceding sections.

It may be summarized as follows[a];

I. "Alternating-current distribution is recognized as desirable because it is considerably cheaper than direct-current distribution and adequately meets the requirements of most consumers. 2. New networks are being laid down on the alternating-current three-phase, four-wire system which enables both power and domestic loads to be supplied from the same cables. 3. Although it is economically impossible to scrap the three-wire direct-current networks which exist in most of the larger towns, the growth of load during the past few years and the probability of a still greater growth in the future has led to an endeavor to avoid increases in the direct-current system. This is being done either by changing over outlying sections to alternating-current or by gradually superimposing alternating-current networks for dealing with new customers.

4. Existing three-wire direct-current networks in the smaller towns and villages, and in suburban areas where the power load is small, are being changed over to three-wire single-phase alternating-current."

Some details of this general policy are reviewed in the following which refers to conditions in Birmingham, England.[b] The direct-current system in this town became fully loaded and it was a question of I) laying additional feeders or, 2) arranging to boost the pressure on the fringe of the system by means of automatic converting plants.

I. The cost of running a one square inch feeder cable to a point I200 yards from the substation plus the cost of additional rotary converter plant, booster and switchgear in the main substation would amount to £9400.

a) 83-p.338 b) 63-p.529

The annual losses at $\frac{1}{2}$ d. per Kwhr in conversion, boosting and cables amount to £1380

cables amount to	£1380
Capital charges at 8 per cent	£ 752
Total annual charges	£2132

2.a) The cost of an automatic 550 KW mercury arc rectifier equipment with building would be £8200.

Annual losses at $\frac{1}{2}$ d. per Kwhr would be	£270
Capital charges	£660
Total annual charges	£930

2.b) The cost of an automatic 500 KW rotary converter equipment with b building would be £ 6500.

Annual losses at $\frac{1}{2}$ d per Kwhr would be	£ 270
Capital charges	£520
Total annual charges	£790

I t should be noted that the mercury arc rectifier does not show up at its best with low voltages. Besides the price quoted for this equipment is perhaps now relatively too high (from 1925).

Another way of relieving the direct-current network was to transfer power consumers to the alternating-current system. It had been the policy to connect customers with a motor load less than 100 horsepower to the direct-current system, but as the alternating-current mains had been extended practically all over the town, power users with 30 horsepower load or over had been connected to these mains.

The relative cost of service on the two systems, direct-current (d.c.) and alternating current (a.c.) for a consumer, requiring 100 horsepower 1000 yards from the nearest source of supply was as follows:

	d.c.	a.c.
Capital cost of transforming plant and cable	£1950	£1040
Annual capital charges at 10% and annual cost of maintenance and losses.	£277	£140
If cables were available close to the consumer's premises and a proportion of these is allocated for his load, the comparison is	£157	£33

For an outlying residential district a direct-current system fed by feeders from a central rotary converter substation was not suitable, as the load density would not justify the expenditure.

The cheapest form of distribution was a four-wire system, 400 volts phase to phase, fed by three-phase transformers strung on poles at frequent intervals.

The comparison in cost per mile between overhead and underground construction was as follows:

	Size	Overhead	Underground
High-tension Lines	(3 x 0.I sq. inch	£93I	£I804
	(3 x 0.06 " "	£792	£I628
Low tension lines	(4 x 0.I sq.inch	£572	£I73I

A comparison between the costs of serving densely populated districts at considerable distances worked out as follows for two different systems:

		d.c.	a.c.
Total cost		£ I 052 520	£408 790
Kwhrs sold in one year	Kwhr	60 200 000	I00 735 740
Revenue from Kwhrs sold		£546 838	£426 69I
Annual return per £ I capital		I0 sh. 5 d.	£ I 0 sh. I0 d.

General Conclusion The relative merits in economics of the direct-current system and the alternating-current system applied to distribution have now been examined for the conditions in two large countries. The general European practice is to use the latter system for distribution and this is undoubtedly the most economical system for practically all conditions, and it will most likely be the accepted future distribution system.

ECONOMICS OF POWER-FACTOR IMPROVEMENT

General. On direct-current systems there is, of course, no question of power-factor, but on alternating-current systems the power factor problem plays a very important rôle in the operation and economics of these systems.

In order to bring this out clearly let us consider two cases. Let the first case be a distribution system with an investment of \$50,000,000.[a] The improvement of power-factor from 0.75 to 0.90 would enable the system to carry an additional load which would correspond to an investment of \$8,000,000.-¶ Let the next case be a town with two power stations, one of a capacity of 80 000 KW, the other of 20,000 KW. These two stations are connected with a cable which can carry at least 5000 KW. Suppose the power-factor of the entire system was raised from 0.8 to unity, then the 20 000 KW could be dispensed with or would be available of supplying energy to an additional load of I5 000 KW. "A station of that capacity represents a capital expenditure of about £450 000."[a]

Causes & Effects of low power-factor. Low power-factor on a system is caused mainly by the use of induction motors. Small fractional horse-power motors of this type are used for driving such equipment as electric refrigerators, oil burners and the like. These motors have a very low power-factor and the increasing use of them is tending to create a serious problem in the residential distribution districts. Also large induction motors have a low-power factor when not fully loaded.

The principal bad effects[b] of a low power-factor are:

I) Increased investment required to provide for a given load because of greater KVA capacity of the system. The necessary increase of K V A capacity is caused by:-

a. A low power-factor load demands greater KVA than a corresponding high-power load factor.

a) 103- p.675 b) 104-p.596

b) The greater reactive drop in the system requires more generating capacity.

c) The losses are also increased by low power-factor and these KW losses must be delivered by the generating stations.

2. Increased Kwhr losses per KW delivered.

3. Greater requirements for voltage regulation.

Means of improving the power-factor on a system.

Power-factor correction can be handled in two different ways:-

I) By installing static condensers or synchronous condensers at certain points of the distribution system or in the substations. This method only corrects the power-factor in the lines between the substations and the generating station.

A rotary converter is essentially a power-factor correcting machine. An average power-factor of about 0.93 is obtained on some primary distribution systems where a large direct-current load is supplied through rotary converters.

2) A more rational way is to improve the power-factor on the customer's premises. This can be done;

a) by installing small condensers near the induction motor. This method does not affect the characteristic of the motor;

b) by using phase-advancers, either of the rotating type or the vibrating type. This method may be used on large induction motors and its function is to supply to the rotor the magnetizing current of the motor so that this current is not drawn from the mains. This method improves the efficiency of the motor,

c) by using synchronous induction motors which besides doing work can be made to improve the power factor of the system considerably;

d) by loading the induction motors to full capacity.

It is seen that there are two classes of apparatus. The first type (static condensers) is used solely for power-factor improvement. The other type (synchronous motors) does work and incidentally improves the power factor. It is not economical to go to the limit in power factor correction by improving the power-factor to unity, because it takes nearly four times as great a wattless component of the current to change the power-factor from 0.8 to unity as would be required to change it from 0.8 to 0.9.

<u>Study of power-factor improvement</u>. Both the power company and the consumers are interested in improving the power-factor of their systems. The power company is interested because a high power-factor improves operating conditions and effects system economy. The consumer is interested because most companies encourage high power-factor by giving a rate advantage to customers having power-factors above a certain limit.

This is accomplished in a number of ways:

a) by giving bonus for high power-factor
b) by penalizing low power-factor
c) by basing demand charge on KVA demand instead of KW demand
d) by charging for KVA hours instead of KW hours

"Low power-factor represents one of the big economic wastes in the electrical industry.

In a study of the costs of low power-factor and the cost of correction, engineers are called upon to evaluate the cost of redesigning, reconstructing or purchasing equipment for correcting power-factor and to weigh the cost of delivering service at low power-factor in comparison to the cost of delivering service at high power-factor. Decisions must be made in regard to apportionment of costs to the utility and to its consumers."[a)]

a)102 - p.135

INTERCONNECTION OF POWER SYSTEMS

Interconnection is usually considered as a transmission problem and quite particularly in relation to the development of a "super-power system." Interconnection has made such a system possible and long-distance transmission has made an extended plan for interconnections practicable, but fundamentally these two problems are independent, and therefore interconnection will here be considered largely in the light of distribution.

There are two types of interconnection: One is the interconnection of distribution systems which has for its "object the tying together of many small and scattered plants and the connection of such a network to a group of efficient generating stations. It is in the development of this type that the holding companies did such pioneering and lasting service."[a)]

The second type is the interconnection of normally independent systems where the main purpose is mutual aid in case of emergencies. Thus each system needs less reserve capacity and yet the reliability of service is better. But in the development of this phase of interconnection certain other factors became of importance such as the interconnection of hydro-electric plants and steam plants, whereby there is a possibility of saving in fuel during certain periods because the most efficient station may carry the whole load and a greater over-all plant economy may be reached.

Another important economy is effected because of improved load-factor which is the quotient of the average load for a certain period divided by the maximum load. This load-factor is usually greater for large systems than for small ones because the maximum demands of a great number of customers are not likely to occur at the same time. The diversity factor measures the effect of this non-coindidence of load by being defined ~~it~~ as the ratio of the sum of the maximum demands to the maximum demand of the whole system.

a) 106 - p.221

191

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a) 126-p.221

To illustrate the importance of diversity of loads and the economy of interconnection an example from the West will be given.[a)]

San Francisco used electricity for lighting and power and has its maximum demand in December. The Santa Clara valley is a rich orchard section, which begins where the metropolitan area ends. The maximum demand in this valley comes in May and June when enormous quantities of water are pumped to irrigate the orchards. Without interconnection the service of each would require a large additional expenditure for steam-electric supply.

Interconnection dovetails the demands of both sections, reduces the investment necessary to supply the service and makes it possible for both areas to obtain electric power at a cheaper rate.

The development of interconnected systems is characterized by the following features:[b)]

I) Erection of highly efficient central generating stations of enormous size. These superstations can be located at considerable distance from the large cities where real estate is cheaper.

2) Consolidations of town plants to form district power systems, supplied from the central stations.

3) Interconnection of district systems for the transfer of power between them to balance the demands of one system as against the other.

To sum up, the underlying economic principles of interconnection and the development of a superpower system are:[c)]

I) "Protection of continuity of services;

2) diversity of load resulting in improvement of load-factor and conservation of capital;

3) diversity of generating supply by combining storage water power with run-of-the-river water power and steam plants at large load centers;

4) pooling of reserve capacity, which reduces the amount of reserve necessary for equal protection, thus conserving capital;

5) relaying of power in case of drougth, high water, break-downs, or other abnormal conditions."

a)105-p.138 b)106-p.225 c)13-p.193

The advantages of such a superpower system have been pointed out by General Guy Tripp:[a)] " A superpower system will permit electrification of many of our railroads and will also reduce the tonnage of fuel to be hauled; thus the efficiency of our transportation system will be improved. It will tend to draw people out of congested districts, save the farmer from many of his labors difficulties and reduce the price of fertilizer because of ample supply of cheap power."

a) 82-p.4.

CHAPTER 3

TRANSMISSION

General

In the early days of commercial utilization of electrical energy it was the practice to build the power stations small and to place them as near as possible to the load center.

This practice arose more from necessity than from desire or premeditation. In the first place there was no need for large power stations, because the demand for electric service had not yet become universal. In the second place, the art of electrical machinery was not developed enough to build large power plants.

These small power stations were placed as near as possible to the centers of population and of load, because it was most economical for the reason that such machinery as is necessary for the transmission of electrical energy had not yet been developed.

From 1880 to 1890 a transmission system was developed in Europe, using high-tension direct-current at 2400, 10,000 and 12000 volts.[a)] In 1902 a line was constructed from St.Maurice to Lausanne transmitting 150 amperes at 27000 volts.

At this time it was generally thought, at least in Europe, that long distance transmission at high pressures would in the future be by ~~continuous~~ direct-current and several important installations of this kind were made in the following years.

There are at present about 16 separate high-tension direct-current transmission lines in operation in Europe, namely in Switzerland, Italy, France, Hungary, Spain, Russia and England. The longest is a 124 miles straight transmission line from Moutiers to Lyons transmitting 150 amperes at 100,000 volts.[a)]

In most of these systems the secondary distribution is low-tension three-phase alternating-current.

Despite of the fact that there are many advantages to high-tension direct-current transmission, no new installations have been made for some time, although several projects

a) 75-p.354

have been contemplated. In America no installations of this system have been made. The reason for this is not due to the inferiority of direct-current transmission in itself, but the difficulties arise at the sending and receiving ends of the system because no really practical apparatus for raising and lowering the voltages at these points have been developed and been tested in actual operation.

In recent years the rapid development of high voltage direct-current machinery makes it possible that a radical change in transmission practice within the next twenty or thirty years will take place, despite the enormous and ever-growing capital investment in the three-phase high-tension transmission lines.

A practical system for the transmission of three-phase current was first developed by Dobrowolski and Ferranti[a)] and the simultaneous introduction of an almost ideal medium for raising and lowering the voltage, namely the static transformer, led to the rapid use of alternating-current for long distance transmission of energy, and the development of the polyphase induction motor, which greatly increased the demand for electrical energy, precipitated the introduction of this system.

The facts that it is possible to insulate transmission lines for very high voltages, and ~~also~~ that the alternating-current transformers is such an ideal device for raising and lowering the voltage at the sending and receiving ends of a transmission line, account for the predominant use of alternating-current for long distance transmission.

For economic reasons it is desirable to use almost as high a voltage for transmission as feasible, because the line losses are inversely proportional to the square of the voltage for the same amount of energy.

a) 75 - p. 354

To illustrate, let I be the amperes of current in a line with a resistance R ohms. Then the line losses are I^2R. - Suppose, now, that we use a pressure ten times as high and transmit the same amount of energy over the same wire; the current will then be $1/10 \cdot I$ and the line losses $1/100\, I^2R$.

At present the highest voltage used is 220,000, but it is possible that as high as 1,000,000 volts might be used in the future for extra-long distance transmission.

However, it is not practical to generate or to use such high voltages as are desirable for transmission purposes and, therefore, an economical and simple medium of raising the voltage is essential.

The low first cost, negligible maintenance cost and high efficiency of the static transformer makes this the cornerstone of present day long distance transmission and has also revolutionized the old time generating station practice.

It is possible now by means of the high voltages used in transmission to locate the generating stations, where coal and water for condensing purposes are most easily obtained and at lowest cost; and the high voltages make it possible to build larger and more efficient central stations for the supply of a large area.

The high voltages have also made it possible and economical to develop water power resources for the generation of electrical energy at places remote from the utilization of such energy. The remoteness of such water power resources has been and still is a contributing cause for the running to waste of enormous quantities of water, which is a potential source of energy that can only be utilized by hydro-electric developments.

The high voltage transmission lines have furthermore made possible the coordinated operation of steam plants and hydro-electric plants in

[illegible]

different locations by means of interconnecting lines.

By this cooperation the more efficient plants can be used at full capacity and the less efficient plants can be shut down at times of low demand. Several more advantages of interconnections will be enumerated in a subsequent chapter which will show the reasons why a gigantic power system has been developed in recent years, particularly in the United States. The future will probably see a still greater growth of this "superpower system," which in the United States may embrace the whole country and which in Europe may tie different countries together in a comprehensive power network.

ALTERNATING - CURRENT TRANSMISSION AT DIFFERENT VOLTAGES

The desirability from an economic viewpoint of using as high voltages as feasible for long distance transmission has been pointed out previously. It was also mentioned that there are economic and practical considerations, which limit the voltages actually used.

Such considerations are, as far as the transmission line proper is concerned, the greater cost of insulators for high voltages and the larger towers which are required due to the increased spacing required between the conductors themselves and between the conductors and ground. As far as the generating and transforming stations are concerned it is the increased costs at higher voltages for apparatus and buildings.

Therefore, there is a certain voltage for each particular transmission beyond which nothing can be gained in the matter of economy.[a] This limit of voltage for the economic operation of a transmission line is called the economic voltage. At lower voltages the principal loss of power is the heat dissipated on account of the watt-losses of the line, and this is proportional to the square of the current and the resistance of the conductor. To reduce these losses, higher voltages and correspondingly lower currents are desirable. This latter permits the use of a smaller conductor area. But as this is reduced and the voltage increased some other losses enter into the picture, namely, the corona losses in the surrounding air. To reduce these losses larger conductor areas are called for. - Another loss of power which increases with the voltage is caused by the leakage current over the insulators.

Thus it is seen that the determination of the most economic voltage and the most economic conductor area is a compromise between several counteracting influences. The size of the most suitable conductor can be determined properly only after the voltage is fixed and when starting on the problem we do not know the voltage. Therefore, it

a) 75 - p. 58

[illegible]

will be realized that the problem is a difficult one to solve. But for any given line operating under definite conditions there is only one particular size of conductor, which is economically the right size and similarly there is a certain most economic voltage and a certain most economic spacing of towers.[a)]

For the determination of these fundamental features of the most economic transmission line for a certain condition one must consider not only the above mentioned factors, but in fact put all expenditures on an annual basis.

Such expenditures are:[a)]

I. Direct expenses:
   a. The yearly cost of energy loss in transmission.
   b. The yearly cost of energy loss in generators and transformers (The efficiency of the electrical plant will not necessarily be the same for different voltages)
   c. The yearly cost of maintenance of the physical plant.

II. Indirect expenses:

   a. The yearly cost of interest, depreciation of the physical plant. (The cost of the physical plant is not only the cost of the transmission line proper, but all capital expenditures, whether for generating stations, transmission lines or receiving stations, which is not constant for all voltages.)
   b. Taxes, insurance, etc.
   c. Future development of apparatus and the possibility of plant becoming obsolete.

To give an illustration of the dependence of first cost of physical plant upon the voltage the following table[a)] shows the approximate costs per kilowatt of a 10,000 KW hydro-electric station.

	Transmission line	←voltage	
	33 000	66 000	110 000
	Cost	per kilowatt	
Power station building, including excavations	$9.90	$10.00	$10,10
Receiving station buildings, including substations (if any)	2.95	3.00	3.15
Switchgear (both ends of line)	1,75	2.00	3.00
Lightning arresters	.55	1.00	2.00
Transformers (both ends of line)	8.20	9.50	12.00
Cables in buildings, bushings, etc.	2.00	2.00	2.50
Crane, sundries, preliminary work	4.80	5.00	5.25
Generators and exciters	15.00	15.00	15.00
Turbines and hydro-electric equipment	16.00	16.00	16.00
Total cost per kilowatt	$61,15	63.50	69.00

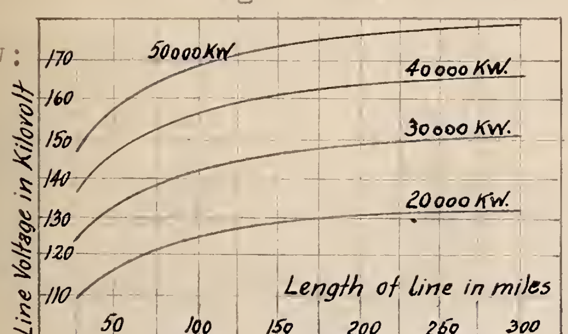
a) 75-p.58

In order to determine the most economic transmission line for a certain condition, it is usually necessary to calculate very carefully the annual costs of different schemes. To start with, it is necessary to know the following data:

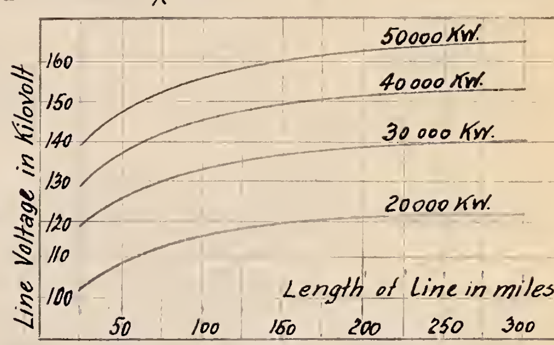
Electrical data: a. System to be used and frequency
b. The power transmitted in KW at a certain power factor

Construction data: a. Length of transmission line
b. Physical conditions along same
c. Certain norms for the determination of the mechanical strength of conductors and towers

Then it becomes necessary to find reasonable voltages for which the different estimates should be made. A great help to this can be had from curves that give a relation between most economic average voltage for certain lengths and amounts of power.[a)] Two such systems of curves are shown below:



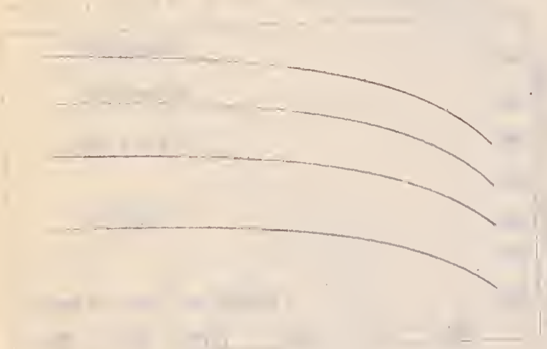
Most economic voltages for Steel-Core Aluminum Lines

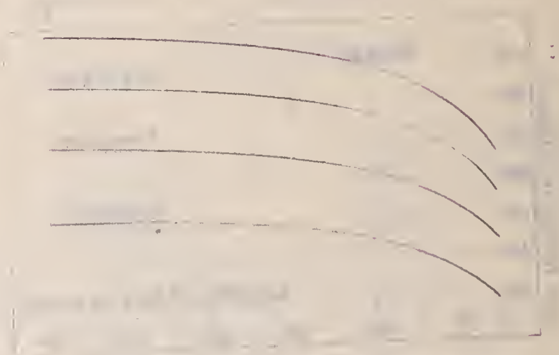


Most economic voltages for stranded-copper lines

An approximate economic conductor size is in the case of steel-core aluminum a circular mills area = $15.8(\text{Kilovolt})^2$ and in the case of stranded copper lines a circular mills area = $17.9(\text{Kilovolt})^2$. It is seen that the most economic conductor size is different whether aluminum or copper is used as conductor material. This point will later be more fully discussed. The curves are based on the Kelvin's law, which requires that the value of the energy annually wasted as line losses be set equal to the annual charge against all variable items of conductor cost, line cost, and terminal equipment cost, whose values vary with either conductor area or line voltage. By expressing these items in mathematical form it is possible to put up an equation, which gives a relation between line voltage, length of line and power to be transmitted. The curves shown are a graphical picture of this equation.

a) 80-p.563





ALTERNATING - CURRENT TRANSMISSION FOR DIFFERENT SYSTEMS.

Three-phase transmission is superseding other systems of alternating current transmission because of the great flexibility of the three-phase system, the balanced condition of voltage and its advantages with respect to the use of both induction and synchronous machinery.

In relation to the two-phase four-wire systems it has a smaller number of conductors and in relation to the single-phase system it has 32 per cent (100:75) = (132: 100) higher copper efficiency as shown in the tabulation[a] below:

	Relative current per wire	Relative voltage between wires	Relative loss per wire	Total relative conductor weight
Single-Phase	100	100	100	100
Three-phase	57.7	100	66.7	75

This is based on same voltage between wires, same transmission distance, same power transmitted and same power losses.

The single-phase system is little used for power transmissions over great distances because the copper efficiency is only 75 per cent of that of the three-phase system for a given voltage between lines and because the single-phase motor is less satisfactory for power purposes than the polyphase motor.

However, in many railway installations in Germany, single-phase transmission is used and in Switzerland there is a single-phase transmission line 216 Km long using a tension of 132 KV, 16-2/3 cycles.

It would, therefore, be of interest to compare some data on <u>first cost</u>[b] of a certain transmission line using either of the two systems. Let us assume that the length of the line is 100 Km and the copper used has a cross-section area of 120 m m^2.

a)/81 - p.916   b)/142 - p.397

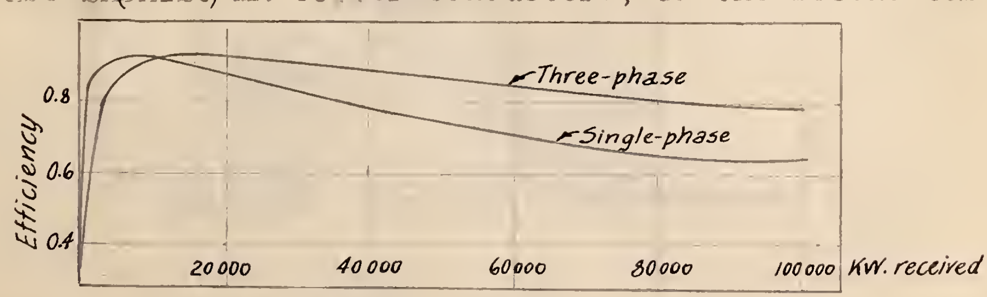
		Three-phase 50 cycles	Single-phase I6-2/3 cycles
Length of transmission line	Km.	I00	I00
Voltage between wires at receiver end	V.	I00,000	I00,000
Voltage to earth	V.	57.750	50 000
Total no-load current	Amp.	5I.6	5
No load power (due to charging current)	KVA.	3000	500
Cross section copper	m m²	I20	I20
Number of conductors	--	3	2
Total copper weight	tons	324	2I6
Height of towers	m.	25	22
Iron weight of tower for same tensile strength	Kg.	2330	I650

It is seen that the single-phase transmission for this purpose as regards the first cost of the transmission line proper compares very favorably with the corresponding three-phase transmission.

The efficiency of a transmission line is expressed as

$$\frac{\text{Power Output}}{\text{Power output plus line losses.}}$$

Let us compare the efficiency of a certain transmission line for different amount of power received. a) Assume the tension is I00 000 volts; then the greatest length of line for this voltage is about 300 km which is taken as the length of the line considered. The power-factor at receiving end is assumed to be 0.8 inductive and we will use the same amount of copper for the transmission of either three-phase, 50 cycles or single-phase, I6-2/3 cycles, namely in the first case 2x(3xI20) mm² copper conductors, in the second case 3x(2xI20) mm².



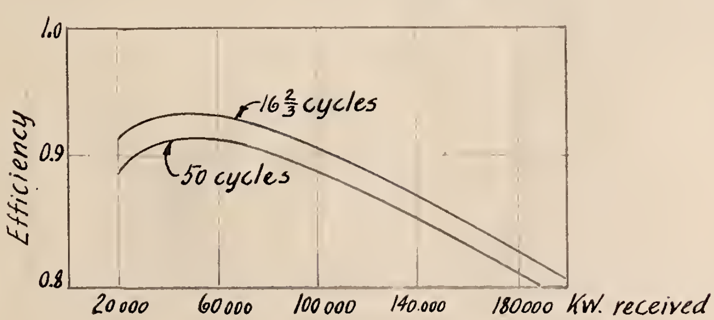
From the diagram is seen that the efficiency for three-phase transmission is fairly high throughout the range of power transmitted. The efficiency of single-phase transmission falls off considerably for higher amount of power transmitted.

Only for power below I0 000 kilowatt is it more economical as far as efficiency goes to use the single-phase system and, therefore, a comparison of the economy of the two systems depends upon the amount of power consumed by the railway. For the conditions in Germany and Switzerland it is apparently most economical and most desirable to use isolated railway power transmission systems with single-phase transmission.

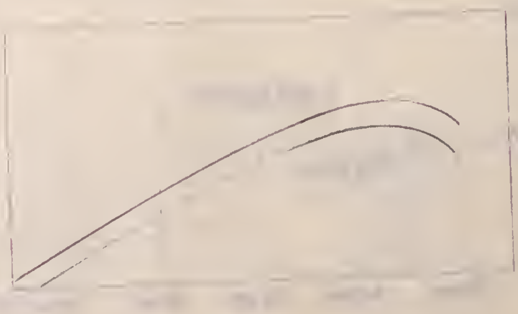
The effective resistance of a conductor rises with the <u>frequency</u> and, therefore, the efficiency drops with higher frequencies. It might therefore be feasible to use one frequency which is desirable for distribution and another lower frequency which is most economical for transmission purposes.

Let us compare the efficiency[a] of a line I000 km long and transmitting I50 000 kilowatt at a tension of 220 000 volts by means of 2x240 mm^2 steel-aluminum conductors and using either a frequency of 50 cycles or of I6-2/3 cycles.

The efficiencies in the diagram below are plotted in relation to power received at the end of the transmission line.



a) 84-p.1061



It is seen that the transmission of alternating current at I6-2/3 cycles is somewhat better than at 50 cycles as far as efficiency in transmission line proper is concerned.

However, this slight advantage is more than offset otherwise, since the I6 -2/3 cycles alternating-current must be converted into 50 cycles at the receiving end by means of motor-generators in order to be used for lighting. Furthermore the cost of machines and transformers at smaller frequencies is considerably higher than the cost at higher frequencies

It may be mentioned that the corona losses, which will later be dealt with, decrease when the frequency is reduced. Thus it may be possible to operate a transmission line at a higher voltage for a lower frequency. (continued on next page)

There are two points of interest, in connection with transmission at lower frequencies which may in the future become of major import - ance. One is the power-factor correction, the other the stability problem.

The power-factor is the ratio of the actual power transmitted to the apparent power, which latter is the product of the root-mean - square value of the voltage by the r.m.s. value of the current in the circuit.

The power-factor may be anything from zero to unity, but is for most commercial applications around 0.8-0.9. Very considerable economics may be effected by having a good power-factor, that is a power-factor as near unity as possible, because at this power-factor there are minimum power losses in the transformers and at any point along a transmission line. Besides a high power-factor gives increased kilo-voltamperes capacity of the line.

Means of correcting the power-factor will be discussed later. Here shall only be mentioned that a frequency changer set is one such means.

It has been pointed out previously that the efficiency of a transmission line increases with lower frequencies because the line reactance and therefore the effective resistance is reduced. An advantage gained by this would be lost - it was stated- by the additional frequency changer sets required for obtaining commercial frequencies.

However, by long transmission lines the power factor correction becomes a necessity and therefore, as frequency changer sets might be used for this purpose, it is conceivable that their cost and the use of lower frequencies may be warranted by a better power-factor and a higher efficiency.

This stage has not yet been reached, but some calculations[a] have been made showing that if lines are built having lengths as great as 500 miles the use of frequency changers may become economical.

The other point of interest was the stability problem and in connection with this the voltage regulation. It is usually required that the voltage at the receiving end shall remain constant at all loads and power-factors and it is desirable because it increases the efficiency and capacity of the line. To accomplish this voltage regulating special synchronous apparatus are installed at the receiving end. The main disadvantage of this scheme is the large cost of such equipment, the main advantage for long lines is the increased capacity for stable operation.

By using lower frequencies the limit of stable operation of the line is increased.[b] "Even a slight decrease in frequency, from 60 to 50 cycles per second, has a considerable effect in improving the operating characteristics of long lines, and this is one of the greatest benefits of the use of 50 cycles in parts of Southern California, where long distance transmission of considerable amounts of power has been found désirable."

"This frequency is high enough to be satisfactory for general lighting and power use, and at the same time offers a considerable advantage over 60 cycles for long-distance transmission."

"Since we seem to be about to enter upon a phase of development in long distance transmission in which stability and synchronizing power are going to be of vital importance, care must be exercised to avoid keeping too nearly in the rut of previous practice, and to keep an open mind for the consideration of changes in practice of fundamental importance, should they become desirable.

"For example, it is not at all improbable that periodic loading of lines with series condensers may be resorted to, to decrease the inductive reactance, just as periodic loading of a telephone line with

a) 82-p.151 b) 82-p.152

inductance is used to increase the reactance. The benefits of a capacitance loaded line are greatest at the higher voltage, and when 330 000 volts is realized commercially in long lines, such loading will very possibly be of economic advantage."

ECONOMIC PRINCIPLES OF POWER-FACTOR CORRECTION IN TRANSMISSION SYSTEMS

The economics of improving the power-factor has been considered previously in connection with distribution. When considered in the light of transmission the problems, means and aims are somewhat similar although of different importance, in the two cases.

The fundamental principle is increased economy, but closely connected with that is the problem of voltage regulation.

There are various means of increasing the economy of a transmission line. First, the voltage may be raised which reduces the current and the losses for the same amount of power transmitted. Second, a large conductor may be installed, which reduces losses. Third, the power-factor may be improved by installing either synchronous or static condensers.

a) The second scheme should not be overlooked, because it has the advantage over the installation of synchronous condensers that there is by the latter method the possibility of the machines falling out of synchronism or giving trouble through hot bearings, etc., ~~so~~ therefore, increasing the copper cross section may give a better assurance of satisfactory service.

The static condenser does not give rise to such accidents as mentioned above, but this apparatus is not as flexible in operation as the synchronous condensers, by means of which the power-factor can be given practically any value, and, besides, the static condenser is more expensive to install on large power systems.

However, by installing static condensers all along the transmission line the power-factor may be improved uniformly and as the power-factor may vary considerably from one end to another on long lines, this may be important because the losses are at a minimum at any point of the system when the power-factor is unity all over. It may be practi-

a) 75-p.67

cable in the future to load extra-long lines periodically with static condensers in order to increase the capacitance of the lines just as the reactance of modern telephone lines is increased by periodic loading with induction coils.

Voltage regulation is accomplished through the improvement of the power-factor. Good voltage regulation is just as essential for satisfactory service as a minimum of interruptions and only by giving good service can the company create the good will of its consumers, which may be of paramount importance in case the company should ask for an increase in rates.[a)]

[b)]"Apart from voltage regulation, the main points to be considered in determining the proper type of corrective apparatus and the amount of power-factor correction which will be economical are:

I) The annual cost of the corrective equipment.
2) The annual cost of the energy losses in same.
3) The annual saving through the reduction of line losses.
4) The annual savings in transformer losses.
5) The annual increase(if any) of operating expense due to the installation of power-factor correcting devices."

a) 82-p.146 b) 75-p.67

EFFECT OF CORONA ON TRANSMISSION LINE DESIGN

General The phenomenon, which is called corona, is observed on transmission lines of high voltages. Above a certain voltage and under certain circumstances there may be seen a faint violet light around the conductor, a hissing sound may be heard and at the same time the characteristic odorr of ozone can be detected.

This phenomenon occurs when the electric gradient set up by the electric field around a conductor exceeds the break down gradient of air and the air becomes ionized and conducts electricity. As the electric field decreases with the distance from the conductor this effect becomes smaller and at a certain distance the electric gradient is less than the breakdown gradient of the air.

Thus at high voltages there will be a conductive layer of air in the form of a cylinder around the conductor and its thickness depends upon the value of the tension, the diamenter of the conductor, the distance between conductors and to a smaller degree upon the frequency of the current, the density of the air, the surface of the conductor and meteorological conditions.

Above a certain voltage, the visual critical voltage, corona appears all along the line. This voltage depends upon the same factors as mentioned above and is particularly much influenced by weather conditions. During snowstorms the usual value may be decreased 20 per cent.[a)]

If the potential difference between the wires is raised sufficiently the corona envelope will grow larger and larger until the point has been reached when an arc occurs.. But even at lower voltages there is a certain leakage current between the wires because the air is always ionized to a slight extent. This leakage current is usually of small import.

a) 51-p.106

Also with direct-current corona may be observed, but the corona appears differently on the two wires. The positive wire has a uniform glow about it, while the glow about the negative wire is more spotty. These same phenomena may be observed with alternating-current if the wires are viewed through a synchronous shutter, so that the wires are seen only when they are at a positive potential, or only when at a negative potential. It is plain that corona only occurs during the time of each period where the momentary value of the tension exceeds, say 30000 volts, the critical voltage. This has a serious influence on telephonic interference, since it causes a deformation of the voltage curve because of the introduction of higher harmonics.

Consequences of Corona Corona causes an energy loss due partly to the liberation of heat and light. This loss can be measured by a watt-meter connected in a circuit with corona and it indicates that power is being supplied to the corona. The leakage current mentioned above also causes some losses.

The main loss is probably due to the charging current caused by the increased capacity of the line.[a] The conducting ionized layer around the wire increases the diameter of the conductor and thereby the line capacity and the charging current. The charging current goes primarily in the conducting air layer and as this has a high resistance and the current density may be great, the energy losses under certain conditions may be considerable. During a snowstorm the corona losses on a 220 000 volts line 375 miles long may be 5600 kilowatt.

ADVANTAGES AND DISADVANTAGES OF CORONA

"Corona has many disadvantages,[b] and while it may be questioned whether or not there are any positive advantages produced by its actual formation, there is no doubt that there are certain advantages

a) 51-p.106 b) 82-p.107

attendant upon the designs which result in corona formation, as compared with designs which would avoid it. In the correct design of a high-voltage line, therefore, a balance should be struck between the advantages and the disadvantages.

"It is generally desirable to avoid corona loss for all fair weather conditions. This can usually be done without great expense because the power transmitted in general requires a conductor large enough to meet this condition. If the condition is not met in this way an aluminum conductor with a steel core or a copper conductor with a core could be used.

"The disadvantages are:

I. Power loss in corona envelope.

2. Production of harmonic voltages and currents, causing lowered useful output or increased losses in connected machinery, and troublesome inductive interference with neighboring communication circuits.

"The advantages are:

I. If the best design for a line is worked out, considering everything except corona, and a further calculation shows that corona will be present on this line as designed, the construction of the line redesigned so as to avoid corona will be more expensive, because either a larger spacing must be used (necessitating more expensive towers) or a larger conductor must be used.

2. If, instead of a redesign of the line, it is decided to operate the line as originally designed at a voltage low enough to avoid corona, the transmission efficiency will be lowered on account of the increased copper loss for the same delivered power, and, further, the maximum kva capacity of the line will be lowered.

[illegible]

3. It has been suggested that it might be advantageous to operate lines at or near the critical voltage, so that when the voltage rises above normal due to transient conditions, the extra charge on the line will be quickly disposed of by corona leakage. The corona might be expected to act like a safety-valve, and allow the voltage to return quickly to normal, thus preventing much extra strain on the insulators. The benefits of this scheme are as yet somewhat problematical. One objection is that the critical voltage varies considerably with weather conditions.

Transients are without doubt reduced by corona. However it is probably better (less expensive) to operate 10 per cent below the corona starting voltage than 10 per cent above. This would only make a difference of 20 per cent of line voltage at which the transient voltage started to cause "transient" corona loss.

"No categorical design rules can be given regarding corona, except the general principle of design for minimum total annual cost, interpreted in a broad way. Each line presents a problem in itself different from all others, and two apparently identical transmission projects in different parts of the country might require different treatments of the corona problem, on account of different climatic conditions. In a region where there are only a few storms each year on the average, it might be wise to allow considerable corona loss on these rare occasions, so as to enjoy the continuous benefits of the higher voltages without increasing too much the cost of construction."[a]

[a] 82-p.107

[illegible]

COMPARISON BETWEEN COPPER AND STEEL-ALUMINUM AS CONDUCTOR MATERIAL

Aluminum is employed on an increasing scale in the construction of modern electrical transmission lines. In all parts of the world there are extensive aluminum transmission lines for the transmission of energy over great distances. Aluminum has for such purposes to a large extent substituted copper, which up to a recent time was used almost exclusively. The reason for that is, that copper is not as economical as aluminum for tensions of 100 000 to 220 000 volts, and aluminum has also proved to be technically superior to copper and probably to any other conductor material.

The high voltages used in modern transmission practice require very expensive insulators and also large towers. To reduce this cost the tendency is towards using as few suspension points as possible, that is to suspend the conductors over as long distances as possible. This in turn, requires higher tensile strength of the conductor material and they have become so high that aluminum alone does not suffice.

Therefore, a steel-core has been embodied in the aluminum conductor in order to improve the tensile properties of the conductor and lower the temperature coefficient of expansion. In this way a steel-core aluminum cable is a concentric strand consisting of a central core of galvanized steel wires with one or more layers of aluminum wires outside. For extremely high fluctuations in temperature the different temperature coefficients of expansion for aluminum and steel give rise to undesirable differences in the stress-strain of the materials. This circumstance has of late raised the problem whether instead of steel-aluminum conductors one cannot use conductors of homogenous material and the result so far is the development of a certain aluminum alloy the tensile strength of which is 80 per cent higher than by using pure aluminum.[a]

a/85-p.7

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

The resistance of this alloy is only 6 per cent higher than that of pure aluminum and this increase for a high-tension line is insignificant.

Steel-aluminum conductors as they are used to-day are superior to copper conductors for very high voltages, because there is a certain critical tension above which the corona losses begins to increase rapidly. [a] Electrical corona occurs when the potential of a conductor in air is raised to such a value that the dielectric strength of the surrounding air is exceeded. Corona represents an energy loss which on a long transmission line may be substantial.

This critical tension is raised when using a larger cross-section and, therefore, to decrease the corona losses the diameter of the conductor must be increased.

The allowable current-carrying capacities of aluminum wire are 84 per cent of the values for copper wires.[b] Therefore, an aluminum conductor has a larger cross-section than a corresponding copper conductor and hence less corona losses; or in other words for given loss per unit of length the maximum allowable operating tension is higher for aluminum than for copper.

The table below has been calculated[c] for such maximum tensions for a three-phase line with 240 mm^2 per phase. For steel-aluminum the equivalent copper cross-section is given. The distances between conductors are the same in all cases:

Corona losses in KW per Km	L-0	L-2	L-4	L-6	L-8	L - 10	
Copper 3x2x120 mm^2	133.9	145.6	150.7	154.5	157.7	160.5	Kilovolts
Aluminum 3x2x120 mm^2	184.2	194.8	199.4	202.9	205.8	208.4	"
Copper 3x240 mm^2	177.5	193.0	199.3	204.3	208.5	212.1	"
Aluminum 3x240 mm^2	244.5	258.5	264.4	268.3	272.6	275.9	"

Maximum operating tensions in kilovolt for different corona losses per kilometer.

The table brings out how much higher voltage is permissible for aluminum than for copper under similar conditions. Also that by using one large conductor per phase instead of two smaller ones, the maximum

a) 81-p.951 b) 81-p.1085 c) 84-p.1025

voltage is materially increased.

As the power transmitted is proportional to the square of the tension, then it is plain why aluminum is superior to copper as to power transmitted for a certain section.

The table[a] below gives the relative power that can be transmitted with the same lines as above. The amount of power that can be transmitted with copper of 3x2xI20 mm^2 cross-section is set arbitrarily to I00 Kilowatt.

Corona losses in KW per Km	L-0	L-2	L-4	L-6	L-8	L-I0
Copper 3x2xI20 m m^2	I00	I00	I00	I00	I00	I00 Kilowatt
Aluminum 3x2xI20 m m^2	I89	I78	I75	I72	I70	I68 "
Copper 3x240 m m^2	I76	I75	I75	I75	I75	I75 "
Aluminum 3x240 m m^2	333	3I4	307	303	299	295 "

Relation between capacity for transmission of power of copper and steel-aluminum transmission lines at same corona loss per kilometer.

The table brings out for example that with three conductors @ 240 mm^2 there can be transmitted for the conditions given 75 per cent more energy than with the same amount of copper, 3x2xI20 m m^2. And with three steel aluminum conductors of the same equivalent cross-section there can be transmitted from I95 to 233 per cent more power than with 3x2xI20 mm^2 copper.

a) 84- p.1028

DIRECT-CURRENT TRANSMISSION

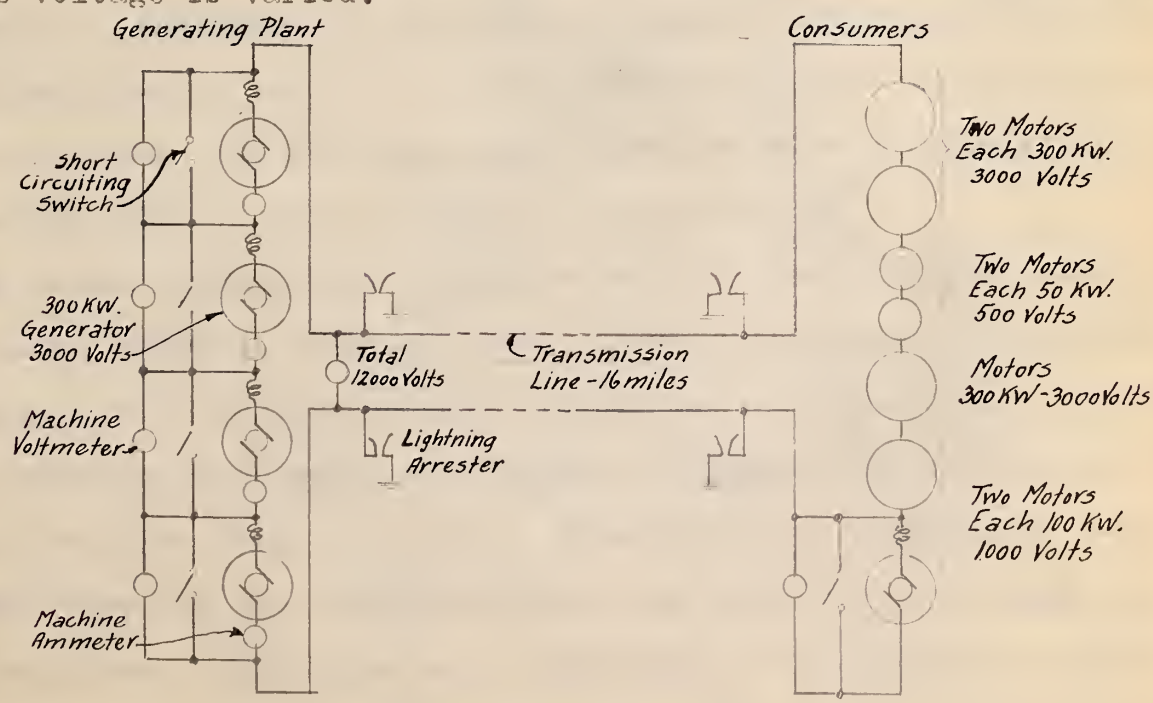
General

In the Thury system of electric power transmission by direct-current, the current is constant in value and the pressure is made to vary with the load. The system is also called the series system, because all the generators and motors are connected in series, this being necessary as the voltage across each generator is limited on account of the commutator, which cannot safely be constructed for more than 5000 volts.

The usual three-phase high-tension alternating-current system is sometimes referred to as the parallel system, since all transformers work in parallel on the system.

Operation of Systems

The diagram below[a)] shows the very simple connections of the series system; it is in fact so simple that it is almost self-explanatory. The operation is such that when the motor load varies, the generators are switched in or out by means of the short-circuiting switches, and thus the voltage is varied.



a) 81 - p. 917

Typical Thury System.

Each generator is mounted on an insulated platform and connected to its prime-mover by an insulated coupling. In this system the current is maintained constant by automatic devices which control the prime-mover speed, shift the brushes and shunt the field; this gives the fine-regulation for varying the voltage with the load. The power is delivered to motors similar in construction to the generators. The motor speed is controlled by shifting the brushes and simultaneously shunting the field.

APPlication of System.

A number of such plants are at present giving satisfactory service and some of those plants are not small either. Line voltages approximating 70 000 volts are in use, and a transmission distance of I24 miles (Moutiers-Lyon) has been reached.

Direct-current transmission is at present limited by the difficulty of obtaining a voltage sufficiently high for economic transmission. It has not been used in America perhaps due to some extent to the fact that is is foreign to American practice, where three-phase alternating-current is considered the only system feasible for transmission. Therefore, it has hardly received any attention at all by American engineers and yet the European practice proves conclusively that the system is not only operative but possesses some characteristic advantages, which are of great import in some classes of transmission.[a)]

The system is admirably adaptable for a long-distance straight transmission, where an isolated power plant is connected to an industrial area. It is an ideal medium for connecting alternating-current systems operating with various voltages and frequencies and located at great distances from each other. Especially where crossings over water are necessary and submarine cables may be the only solution, the system is without doubt superior in operation to the alternating-current system.

a) 99 - p. 350

An outstanding example of a situation in which direct-current transmission was found to be desirable is the installation in London and its environments for supplying energy for lighting and motor service.[b] The special conditions here were such that underground cables were necessary due to the thickly populated territory. Alternating-current underground power cables had not been developed to such an extent that they could cope with the difficulties arising from the long distances and high voltages, but as it is probably as easy to construct a direct-current cable for 66 000 volts as it is to insulate it for 13000 volts alternating-current, the direct-current cables came in as a practical solution of the problem.

The highest operating voltage for which single-phase underground alternating-current cables have been constructed is 132000 volts. Such cables are in operation for three-phase transmission in New York connecting the Hell Gate generating station with a station in Westchester County. Very great difficulties were encountered in the construction and operation of this cable.

Another interesting example[a] is the contemplated transmission of electrical energy from the water-power resources in Norway and Sweden to Denmark, which has no such natural resources and no coal deposits.

The special conditions were such that the frequency of the existing generating stations in Sweden was 25 cycles and the frequency required in Copenhagen was 50 cycles; frequency changer sets were, therefore, necessary for an alternating-current transmission. A still greater difficulty was the crossing of the sound separating Denmark from Sweden where a submarine cable seemed unavoidable. Two schemes for the transmission of power from Norway to Denmark were feasible. One consisting of an overhead transmission line through part of Norway and Sweden and including the above mentioned submarine cable. The other consisting of an overhead transmission line through the Southern part of Norway and thence a crossing of the sea separating Norway ~~and~~

a) 89 - p. 1026. b) 99 - p. 350

from Denmark by means of a very much longer submarine cable. A tension of 220 000 volts was contemplated for the latter scheme. This project will later be reviewed in details.

A commission was appointed by the Swedish and Danish governments for the purpose of investigating a transmission line 200 miles long from a water fall, Trollhättan in Sweden across the strait to Copenhagen, Denmark.

Comparative costs between transmission by alternating-current and direct-current were made for a tension of 90 000 volts and the investigation resulted in favor of the direct-current system using direct-current generation together with transmission on a wooden pole line, a submarine cable being used across the strait. The ground was to be used for the return current.[b] This whole scheme was considered the most economical one and possessing favorable operating features, but the installation has not yet been made in this form. Instead power is now transmitted from another water fall, Lagan, by means of alternating-current and large synchronous condensers are used near Copenhagen for voltage regulation. (See later.)

Still another large transmission project for which the direct-current system was seriously contemplated was the transmission of energy to Paris from the upper waters of the Rhône. Also here it was the desirability of using underground cable construction on certain sections, which made it exceedingly difficult to use alternating-current at any feasible voltage for such a long transmission.

So far as is known to the writer a direct-current transmission line was considered for the transmission of water power from Canada to Boston and New York.

ADVANTAGES OF THE DIRECT- CURRENT SYSTEM[a]

I) Higher pressures can be used for the same line insulation, thus giving smaller transmission losses. Tests by Thury indicated that with given line insulation, the direct-current voltage may be twice the alternating-current voltage. The maximum pressure occurs only during maximum loads.

a) 81-p. 917 & 75-p. 354   b) 89-p. 1026

[illegible]

2) Absence of phase displacement; the power factor is unity. Smaller transmission losses.

3) Reduction of corona effect, that is reduction of energy losses due to dielectric hysteresis (because the highest pressures are used only at full load).

4) Absence of capacity effect and induction trouble, therefore no abnormal pressure surges and voltage rises. Also absence of charging current for transmission line. For high-tension alternating-current lines such demands may be of the order of 50 000 KVA on open circuit.

5) High-tension underground cables can be made up to 200 000 volts direct-current. Such tensions are as yet not possible with alternating current and perhaps not even feasible. The underground cables give the advantage of eliminating difficulties due to storms, etc., therefore cost of supervision and upkeep is reduced.

6) Transmission distance is greater with direct-current than with alternating-current. No problems of stability or power limit.

7) Any class of supply can be given and different alternating-current frequency systems can be conveniently paralleled.

8) Load growth can be taken care of simply by adding a new machine in the generating station assuming the line insulation is sufficient.

9) For any industrial operation requiring a variable-speed drive at constant torque the series-motor is admirably adapted.

10) The rotational speeds of hydraulic turbines on moderate heads are of the same order as those of direct-current machinery.

11) In hydraulic generating stations with variable head a greater all-around efficiency can be obtained for variable-speed generators, since constant speed is unnecessary.

12) A direct-current transmission line is cheaper in regards to copper, insulations and towers, than an equivalent alternating-current line.

13) Line repairs can be easily and safely made, while the line is in operation after grounding the conductor at the point in question. This is, of course, not applicable to systems with grounded neutral or systems using the earth as return conductor.

14) The use of the earth as a return conductor permits a reduction of 50% in the necessary copper for the same tension.

15) By using high-tension underground cables the use of expensive intermediate transformation in crowded centers is avoided.

16) Absence of transformers and synchronous condensers on any direct-current transmission line.

17) The simplicity and relatively low cost of high-tension direct-current switchgear is remarkable.

DISADVANTAGES OF THE DIRECT-CURRENT SYSTEM a)

I) With the constant current on the line, the line losses are constant at all loads and independent of the load, although the current may be somewhat decreased at light load. This inability to give reasonable transmission efficiency at low load factors is a serious objection for the operation of the direct-current system.

2) The series system is essentially a straight transmission system, not a distributing system. The series system cannot be subdivided as the parallel alternating-current system can.

3) A direct-current overhead transmission line is more subjected to damage from lightning than an alternating-current line and, therefore, the cost of protective devices for lines and generators may be considerably higher in the first case. The greater liability of damage to generators due to lightning is a great objection in regard to reliability.

4) All machines and apparatus must be mounted on insulated floors and insulated couplings must be used between prime-movers and generators. This insulation is very expensive and difficult.

5) Smaller prime-movers must be used as the output of each generator is limited by the line current and the voltage used on a machine. Generating units must, therefore, necessarily be of moderate capacity, but several generating units may be connected to one prime-mover. This limitation of the direct-current machines is in opposition to modern practice of using turbo-alternators of enormous size.

6) Transformation requires rotating machines, which are more expensive, require greater upkeep and are less efficient than static transformers.

7) The commutators of the direct-current machines are weak points in the system. They also limit the voltage used on each machine.

8) A machine with a commutator is not well adapted for direct-

a) 88-p.192 & 89-p.1026

coupling to steam turbines of modern design on account of the high peripheral speed. Reduction gearing causes an increase in initial cost.

9) Special regulating devices are necessary if the motors shall maintain constant speed for industrial purposes.

10) The constant-current motor is not adaptable to electric traction systems, as it is not possible to secure an overload torque on the motor even for short periods.

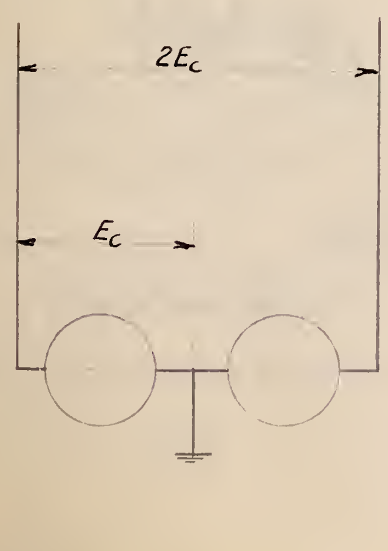
11) The water turbine working under constant head is not the ideal engine for driving constant-current machines (variable speed). This, however, can be remedied by brush shifting devices.

RELATIVE COSTS OF CONDUCTOR MATERIAL FOR A DIRECT-CURRENT AND AN ALTERNATING-CURRENT TRANSMISSION LINE

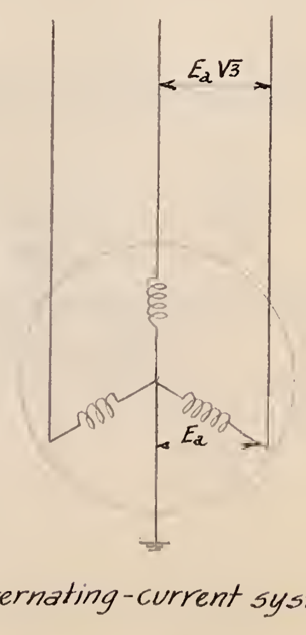
The deciding factor in comparing the series system and the usual parallel system ,the three-phase high-tension system, is the allowable tension between wires or between wires and ground. Assuming a sinusoidal pressure curve the maximum instantaneous pressure value of an alternating-current is $\sqrt{2}$ times the root-mean -square value and tests show that for the same insulation the allowable direct-current pressure is from $\sqrt{2}$ to 2 times the r.m.s. pressure of an alternating-current system. Usually two insulated wires are used for high-tension direct-current transmission, but it does not seem objectionable to use the earth as the return conductor for values as high as 100 amperes. This, of course, would cut the cost of conductors down to one half.

Let us study the relative cost of conductor material for a direct-current (d.c. cost) and an alternating-current transmission (a.c.cost) over the same distance, transmitting the same amount of power with the same loss in conductors and using the same insulation.[a]

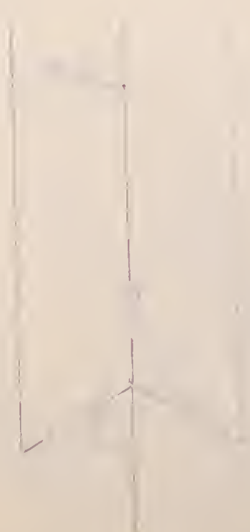
Let E_c be the direct-current pressure to ground and E_a the alternating-current pressure to ground. Then the pressure between the wires is $2E_c$ and $E_a\sqrt{3}$ respectively. [a] 75-p.354



Direct-current system.



Alternating-current system.



Let I_c and I_a, and R_c and R_a be the currents and resistances per conductor of respectively the direct-current and the alternating-current system.

The total cost of conductors for a direct-current line is then proportional to $\frac{2}{R_c}$ and for an alternating-current line proportional to $\frac{3}{R_a}$, where 2 and 3 are the number of conductors for the two systems.

The relative cost of conductors for the two systems is, therefore,

$$\text{a)} \quad \frac{\text{A.C. Cost}}{\text{D. C. Cost}} = \frac{3R_c}{2\ R_a}$$

The same amount of power transmitted is expressed by the equation.

$$2E_c \times I_c = 3E_a \times I_a \cos\varphi \text{ or}$$

$$I_c = \frac{3\ E_a I_a \cos\varphi}{2\ E_c}$$

The requirement of equal line losses gives us the equation $2\ I_c^2 R_c = 3\ I_a^2 R_a$.

We substitute the value found for I_c and find

$$2\ \frac{9E_a^2 I_a^2\ \cos^2\varphi}{4\ E_c^2} \times R_c = 3\ I_a^2\ R_a,$$

which gives us

$$\frac{3\ R_c}{2\ R_a} = \frac{E_c^2}{E_a^2} \times \frac{I}{\cos^2\varphi}$$, or assuming an average power factor $\cos\varphi$ of 0.8 for the three-phase system we find from equation a)

$$\frac{\text{A.C. cost}}{\text{D.C. cost}} = 1.56 \times \frac{E_c^2}{E_a^2}$$

This shows us that the relative conductor cost depends entirely upon the pressures used for the two systems.

Four different conditions will be considered.

1) Same maximum pressure between wires assuming sinusoidal wave alternating-current voltage, and assuming, *conservatively*, that the direct-current pressure can be $\sqrt{2}$ times the r.m.s. alternating-current pressure we have

$$\frac{2\ E_c}{\sqrt{3}\ E_a} = \sqrt{2} \quad \text{or} \quad \frac{E_c}{E_a} = \sqrt{\frac{3}{2}}$$, which gives us

$$\frac{\text{A.C. Cost}}{\text{D.C. Cost}} = 2.34$$

2) Same maximum pressure above ground and same assumption as in I):

$$\frac{E_c}{E_a} = \sqrt{2} \quad \text{and} \quad \frac{\text{A.C.Cost}}{\text{D.C. Cost}} = 3.12$$

3) Same as I) but assuming the allowable direct-current pressure between wires to be double the alternating-current pressure:

$$\frac{2\ E_c}{\sqrt{3}\ E_a} = 2 \text{ and } \frac{\text{A.C. Cost}}{\text{D.C. Cost}} = 4.68$$

4) Same as 2) but assuming the allowable direct-current pressure above ground to be double the alternating-current pressure:

$$\frac{E_c}{E_a} = 2 \text{ and } \frac{\text{A.C.Cost}}{\text{D.C. Cost}} = 6.24$$

These figures show very clearly that an important saving can be obtained in the cost of the transmission line proper by using direct-current transmission, since the cost of conductors of a corresponding alternating-current line was from 2.34 to 6.24 times greater than the former. But an additional saving is effected with a direct-current transmission line, because fewer insulators are required, as there are only two conductors to string instead of three and the towers for a direct-current line can be made lower and lighter than for an alternating-current line.

If a ground return were used, the cost of copper and of insulators as well as stringing would be only one half of the one considered above and therefore the final figures should be multiplied by 2, giving the still greater advantage of a factor from 4.68 to 12.48 in favor of the direct-current system.

Of course, first cost of plant and operating charges must be taken into account when comparing different systems, and the most satisfactory and exact way of doing this is to reduce all estimated costs to the common basis of annual charges.

COST COMPARISON OF DIRECT-CURRENT AND ALTERNATING-CURRENT SYSTEMS.[a)]

A transmission system consists of three distinct features; namely, the generating station, the transmission line proper and the receiving plant.

Regarding the cost of the transmission line proper we saw that under the same conditions it is less than that of an alternating-current line. The possibility of using the earth as one of the conductors results in a very large saving.

The advantage of the direct current system would be very materially enhanced with a project where underground cables are employed No exact data are as yet available as to the relative cost of the cables for the two systems.

As regards the apparatus at the sending and the receiving ends of the line it is astonishing how simple and cheap the switchgear of a direct-current plant is in comparison with that of a three-phase alternating-current plant.

a) 89-p.1026

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

The series system requires practically no switchboard at all and the machines are put into and out of action with the least effort.

Against this the switchboard construction in the three-phase work has become very complicated and burdensome. For instance[a], in the Big Creek plant in California, which transmits three-phase energy of 150 000 volts 240 miles into the city of Los Angeles, one of the three-pole oil-circuit breakers occupies 1200 cubic feet and weighs 14 tons including oil filling.-

After all these beautiful features of the direct-current system it is wholesome to consider its crucial point, the generating station. The construction of this is very difficult and very expensive both on account of the necessary special insulation to earth of all machines, the high cost of the commutating machines, and the necessary governors. Regarding the receiving plants one may fairly compare the motor-generator sets and their switching apparatus of the series system with the transformers of the three-phase system plus their high-voltage switches. As to the receiving plant there is a further point, moreover. In the above mentioned plant in California it became necessary to install two 12,300 KVA synchronous condensers in order to maintain proper voltage regulation at the receiving end. Such a requirement calls one's attention to the fact that the three-phase transmission system has reached a point of development where factors ordinarily of small import become the source of great expense and complication.[a]

a) 99 - p. 350

[illegible]

Such special precautions and the expenses involved should not be overlooked in a comparison and after having taken due regard to all factors mentioned in the different elements of the transmission system, the difference in cost for the two kinds of equipment becomes very much less than would at first seem likely.

In Europe the higher cost of the generating plant has apparently been offset by lighter and cheaper transmission lines and simple switchgear.

Whether the same may be true in America is a question, which only the most careful investigation can reveal.

ECONOMICS OF HIGH TENSION DIRECT-CURRENT TRANSMISSION

The report[a] published by the joint Danish-Swedish-Norwegian commission regarding transmission of electric power from Norway and Sweden to Denmark contains some very interesting data on the first cost and operating cost of different schemes of high tension direct-current transmission as compared with corresponding three-phase alternating-current transmission schemes. Some of these data will be referred to subsequently.

The report also gives some details of the proposed generating station in Norway and of the receiving stations in Denmark, as well as details of operation and regulation.

Regarding the general features of the direct-current system the commission summarizes its advantages over the alternating-current system as follows:

I) No wattless currents.

2) Smaller insulation of lines than for alternating-current at same effective value.

3) No dielectric hysteresis and very small corona losses.

4) Use of two conductors instead of three, that is lighter towers and fewer insulators.

5) Cables can be built for tension of I00 000-I20 000 volts to ground while the limit for three-phase cables is 50 000 volts between phases.

6) The self-induction and capacity of the lines have no influence under normal operation.

7) The stability problem of the parallel system is eliminated.

8) Simple arrangement of apparatus.

9) Simple apparatus for the prevention of interference with communication circuits.

On the other hand the direct-current system is made more expensive by the following circumstances:

I) Generators and motors can be made only of limited size, 250 amperes at 7500 volts pressure. This requires a large number of machines in series.

2) The many commutators require careful attention and maintenance.

3) In the generating and receiving stations an insulated floor must be

[a] 100

[illegible]

[illegible]

[illegible]

1) [illegible]

2) [illegible]

3) [illegible]

4) [illegible]

5) [illegible]

6) [illegible]

7) [illegible]

8) [illegible]

9) [illegible]

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[illegible]

[illegible]

provided for the safety of the personnel.

4) Linelosses are constant at all loads, which gives low efficiency at small loads.

5) Interconnection with existing alternating-current systems can only be effected by means of converting stations.

6) The direct-current system is only adapted for straight power transmission, not for distribution.

The amount of power transmitted to the centers of consumption in Denmark should be, within ten years, 42000 Kilowatt at a pressure of 220 000 to 224 000 volts and 250 amperes, but in the future it may be possible to increase these values to 90 000 kilowatt at a pressure of 300 000 volts and 300 amperes. If the power requirement should be further increased it would necessitate a complete, new plant and line in parallel with the original; thereby I50 000 kilowatt may be taken from the waterpower stations in Norway and about II5 000 kilowatt delivered at three places in Denmark at a pressure of 300 000 volts and at 250 amperes. Thus the efficiency of the whole transmission plant would be 77 per cent.

Four different schemes were considered (refer to accompanying map)

I) Direct-current system with overhead line in Norway and with cable under Skagerak.
2) Direct-current system with overhead line through Sweden and cable under Øresund.
3) Alternating-current system with overhead line through Sweden and cable under Øresund.
4) Alternating-current system with overhead line through Sweden and over Øresund.

Two different water power sources located conveniently are available for the different schemes as shown on the map and the distance to the load centers will be 412 and 605 miles which is about double the distance used up until now for power transmission.

For the first and second schemes a tension of 2xII0 000 volts with grounded midpoint would be used. For the two last schemes I32 000 volts, which is the standard pressure used in Sweden, would be used.

SCHEME I.


NORWAY
SWEDEN
Generating Station
SKagerak
Aarhus
Copenhagen
DENMARK
GERMANY

SCHEME 2

Schemes 3 & 4 similar.

Costs of installation and of operation for the four schemes work out as follows.

1) Direct-current system with cable under Skagerak.

a) Cost of installation of direct-current plant (2x110,000 volts)

		Number	Kroner per meter	Millions of Kroner
240 km overhead line	185 mm^2	3	29.20	7.0
Grounding system	" "	1	-------	0.1
130 Km submarine cable	" "	3	69.00	9.0
Placement of cable		3	-------	2.5
Communication system		--	-------	1.2
Receiving station at Aarhus	5x6000 KVA	--	------	7.0
135 km overhead line	185 mm^2	3	29.20	3.9
60 km submarine cable	" "	3	69.00	4.1
Placement of cable		3	-----	1.0
Receiving station at Copenhagen	5x7000 KVA	--	-----	7.8
Total for straight transmission				43.6

b) Cost of alternating-current plant, primary distribution 50,000 volts

		Number	Kroner per meter	Millions of Kroner
110 km overhead line Aarhus-Aalborg	3x70 mm^2	1	15.20	1.6
100 " " "Aarhus-Kolding	2x3x70 mm^2	1	25.50	2.6
68 " " "Kolding-Odense	3x50 mm^2	1	14.00	1.0
2 " " " " "	3x95 mm^2	2	-----	0.2
Synchronous motors	14 000 KVA	--	-----	0.6
Total for primary distribution				6.0
Total for whole plant				49.6

2. DIRECT-CURRENT SYSTEM WITH OVERHEAD LINE THROUGH SWEDEN AND CABLE UNDER Øresund.

a) Cost of installation of direct-current plant (2xII0 000 volts)		Number	Kroner per meter	Millions of Kroner
645 km overhead line	240 mm^2	3	33.00	2I.3
Grounding system	" "	I	-----	0.I
I5 km submarine cable	" "	3	75.00	I.2
Placement of cable		3	-----	0.3
Communication system		---	-------	I.2
Receiving station at Copenhagen 5x7000 KVA		--	-------	7.9
2I3 km overhead line	240 mm^2	3	33.75	7.0
22 " submarine cable	" "	3	75.00	I.7
Placement of cable		---	-----	0.4
Receiving station at Kolding 3x6000 KVA		--	-----	4.5
I00 km overhead line	240 mm	3	33.00	3.3
Receiving station at AArhus 3x6000 KVA		---	------	4.5
Total for straight transmission				53.4

b) Cost of alternating-current plant; primary distribution 50 000 volts				
II0 km overhead line Aarhus-Aalborg	3x70 mm^2	I	I5.30	I.6
68 " " " Kolding-Odense	3x50 mm^2	I	I4.00	I.0
2 " " submarine cable " "	3x95 mm^2	2	-------	0.2
Synchronous motors ...	5000 KVA	---	------	0.2
Total for primary distribution				3.0
Total for whole plant				56.4

3. ALTERNATING-CURRENT SYSTEM WITH OVERHEAD LINE THROUGH SWEDEN AND CABLE UNDER ØRESUND

a) Cost of installation of alternating-current plant (I32 000 volts)

		Km	Millions of Kroner
Overhead line	2x3xI20 mm² Ø 48.70 Kr per meter	6I0	29.7
Tie-in station at Glommen		----	0.6
Tie-in station at Trollhättan		----	0.6
Transformer station at Hälsingborg 4x50 000 KVA; Synchronous motors	I5 000 KVA	----	3.9
Communication system		------	I.2
Total			36.0

b) Alternating-current plant at 50 000 volts

		Km	Millions of Kroner
Submarine cable Øresund	3xI50 mm²	4xI5	2.7
Overhead lines in Denmark		533	I2.8
Submarine cables in Denmark		67	3.5
4 Transformer stations			I.5
Synchronous motors	30 000 KVA		I.4
Total			2I.9
Total for whole plant			57.9

4. ALTERNATING-CURRENT SYSTEM WITH OVERHEAD LINE THROUGH SWEDEN AND OVER ØRESUND

a) Cost of installation of alternating-current plant (132 000 volts)	Km	Millions of Kroner
Overhead line 2x3x120 mm² @ 48.70 Kr per meter	75.3	36.7
" over Øresund 2x3x110 mm² Aluminum plus 240 mm² steel core	7	4.0
3 tie-in stations in Sweden		1.8
Transformerstation at Copenhagen 3x25 MVA		3.1
Transformer station at Kallundborg 2x25 MVA		1.9
Communication system		1.2
Total		48.7

b) Alternating-current plant at 50 000 volts		
Overhead lines in Denmark	57.8	7.2
Submarine cables in Denmark	67	3.5
Transformer station at Aarhus 2x4 MVA		0.4
Synchronous motors 12 MVA		0.6
Other regulation		0.2
Total		11.9
Total for whole plant		60.6

The efficiencies of the four schemes compare as follows:

Scheme	I	2	3	4
Delivered in Denmark	42 000	42 000	42 000	42 000
Losses in lines and machines	I3 500	I3 900	I7 I00	I0 500
Generated in Norway	55 500	55 900	59 I00	52 500
Total efficiency in per cent	76	75	7I	80

The yearly costs of operation are as follows in millions of Kroner

Scheme	I	2	3	4
Expenses I0% of capital	4.96	5.64	5.79	6.06
Cost of power in Norway @ 80 Kr. per KW year	4.43	4.47	4.74	4.20
Total	9.39	I0.II	I0.53	I0.26
Cost in Kroner per KW year	224	240	25I	244

Summary of Cost of Installation

Scheme	I	2	3	4
Millions of Kroner	49.6	56.4	57.9	60.6

It will thus be seen that the two direct-current schemes are the cheapest both in respect to first cost and cost of operation. This is based upon the assumption that power can be bought for all schemes for 80 Kr per Kilowatt-year, but the commission evidently considers this possible.

It is seen that about one half of the expenses goes to pay the electricity in Norway, the other half being interest and amortization of first cost of installation plus maintenance plus loss of energy.

Despite the difference in cost between the two systems the commission does not make any specific recommendation, as there are considerations other than economic ones which can be advanced for and against the alternatives.

The costs were calculated for the price level existing in the spring of I922 which costs were probably the double of the pre-war cost. When the project is actually carried out it is probable that it can be done at considerably less cost.

GENERAL CONCLUSION.

Direct-current presents undoubted advantages as far as the transmission line itself is concerned by the use of two or possibly only one conductor instead of three as required for the three-phase system, and by the smaller corona losses for given effective voltage etc.; but it has been practically excluded with the exception of certain places in Europe on account of the expense and inefficiency of the generating station and of the converting apparatus at the receiving end.

Therefore, the disadvantages of the direct-current system, with a few exceptions, have outweighed its advantages up to the present, and the three-phase system has fulfilled its object of providing a cheap and reliable supply of electrical energy. That is why conservative engineers hesitate to switch over to a different system and also because of the enormous capital invested in the present power system.

It is possible a) to transmit under favorable conditions 100 000 to 200 000 K W over a distance of some 300 miles with present-day alternating-current equipment.

This will probably also be possible with the direct-current system when certain perfections in the generation and transformation of high-tension direct-current have become materialized.

Such machines have been developed on a small scale and when they can be constructed for larger power output they will probably be cheaper and more practical in operation than a number of series machines.

If those machines live up to what they seem to promise, the direct-current system for transmission will in all probability be an economic possibility, but the realization of such promises seems at the present time rather distant.

a) 87- p.148

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CHAPTER 4

ELECTRIC RAILWAYS

RAILWAY ELECTRIFICATION IN GENERAL

One of the greatest technical economical problems of our time is the conservation of the natural resources. Especially has the question of the exhaustion of existing coal fields made the economizing of coal a problem of world-wide scope.

But besides this a national problem was met in many countries during the world war when they found their coal supply cut off or in the best case the coal prices rose to an unprecedented height which threatened the whole economic life of those nations, and particularly the ~~the~~ transportation problem was a serious one. Thus the question of the electrification of the railways became an actual and pressing one in many countries where the "black diamonds" could be substituted by "white coal", that is, by hydro-electric power.

At the present time railways are being electrified all over the world on an ever-increasing scale and it is, therefore, pertinent to inquire into the general status of railway electrification and the practice in the various countries, particularly so, because no general standard has been accepted.

The following investigation will attempt to point out the reasons for this variance even inside the same country. It is not the object to compare the economics of steam operation with the economics of electrical operation, but it will be assumed that electrification has been found desirable for certain reasons.

Reasons for Electrification of Railways.

Whereas in some countries like France, Italy, Switzerland and Norway the coal problem as pointed out plays a very prominent rôle, this problem does not have the same importance in countries like England and America, but nevertheless also these countries work intensely on the electrification of their railroads.

In the latter countries it is above all the necessity of increasing the capacity of the railways which accounts for the great interest in electrification. The rapidly growing volume of traffic on certain lines would require so considerable enlargements of existing steam facilities that the economy of the railroad would be threatened. Therefore, it becomes necessary to look for other means of increasing the capacity of the railways and electrical operation offers one solution of that problem. This is due mainly to the special qualities of the electrical locomotive, since they influence a number of circumstances in the construction and operation of the railways in such a way that, in comparison with steam operation, facilities and savings are effected which to a great extent compensate for the additional expenses of the electrification.

In other countries it is the problem of steep grades which electric locomotives overcome more easily than steam locomotives, or it may be the problem of abating smoke in tunnels or terminals.

The poor utilization of the fuel in a steam locomotive is not up to modern standards as found in central stations. Therefore, one of the most eminent engineers, Dr. C.P. Steinmetz, has expressed[a)] this by calling the steam locomotive an "anachronism". The special qualities of the electrical locomotive previously mentioned arise mainly from its ability to stand overload for a certain time. During start and acceleration it may be overloaded up to 100% which makes a quicker get-away and speeds up the service, especially where there are frequent stops. For longer periods of up to an hour the locomotive can stand an overload of 15 - 30%, which enables it to surmount steeper grades, or increase the speed, or haul heavier trains than a steam locomotive of same power; all of which increases the capacity and effectiveness of the railway. Besides this, electric operation enables the use of heavier locomotives without changes in roadbed or bridges. A greater proportion of the total weight of an electric

a) 115 - p. 8

locomotive can be used for adhesion as compared with a steam locomotive; thus under similar conditions the electrical locomotive needs less adhesion - weight than a steam locomotive.

The electric locomotive develops a practically constant tractive effort on the wheels, whereas it varies considerably for a steam locomotive; thus under electrical operation the slipping of the wheels is less likely than under steam operation.

To sum up: by electrical operation the trains can run faster or pull heavier trains than by steam operation. And a new railway built for electrical operation can be constructed with about 50% greater maximum grades than if it were built for steam operation. The latter advantage may in rugged countries compensate for the additional expense for the electrical equipment.

Classification of Railways

Very different conditions arise when ~~different~~ electrification of different types of railways is considered. Therefore, it is convenient to group railways in the following classes:

1) Main trunk lines. Long-distance transportation of passengers and freight. The railway owns its own roadbed and the trains run in accordance with fixed regular schedules.

2) Interurban lines. Medium distance transportation (up to 80 miles), primarily of passengers. Light-weight cars running on own roadbed. Fast, regular train service.

3) Railways in urban centers, street cars. Trains run in streets or underground or on elevated structures. Only passenger transportation with light-weight cars. No rigid train schedule, but frequent trains and stops.

CLASSIFICATION OF ELECTRIC TRACTION SYSTEMS

The rolling stock of an electric railway is the characteristic feature of the plant. On the performance of the rolling stock depends the type of equipment to be used, its capacity, speed and power input to the train. This last named factor, in turn, determines the characteristics of the low-potential distribution system, whether trolley or third-rail, and its capacity. This, again, leads up to the determination of substation capacity and, finally, the capacity and cost of the generating station.

Thus the whole system is built up on the characteristics of the motors, and, therefore, it is important that the different types of motive power be thoroughly understood.

a)There are four types of motors available for railway service, giving rise to three systems of distribution:

a) The direct-current series-wound motor used at line voltages of from 600 to 3000 volts. The current is converted by different methods from a high-potential three-phase alternating-current transmission system.

b) The alternating-current series-wound motor fed directly from an alternating-current high-potential transmission system through intermediary step-down transformers.

c) The alternating-current three-phase induction motor fed directly from an alternating-current three-phase transmission system through step-down transformers or without transformers.

d) The alternating-current polyphase induction motor, fed from a single-phase circuit through an intermediate phase converter ("split-phase system")

All four systems enjoy the advantage of alternating-current generation and transmission of power at high potential, the direct-current and induction motor system demanding multi-phase generation,

a)114-p.1358

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while single-phase generation and distribution may be used for the single-phase alternating-current ~~motor~~ and the split-phase systems.

CONSIDERATIONS OF DIFFERENT SYSTEMS

Electric traction was very early used for street railways and the direct-current system was used with a relatively low tension. This system has also been used in connection with third rail on some more important terminal electrifications in New York, Baltimore and Detroit, but when the railways extend over greater distances the low-tension, direct-current system is not economical.

The three-phase system was then introduced in Italy, because of the favorable transmission possibilities of a three-phase system. However, this system has not been used outside of Italy except in very few cases.

The electrification of main trunk lines began first to be actual and gain ground with the development of the single-phase series motor. This motor has almost the same ideal characteristic for traction service as the direct-current series motor, but besides this, it enables the use of a transmission and contact-system, which is considerably more economical than either the three-phase or direct-current system.

It was the Westinghouse-Company's chief engineer, B.G.Lamme, who in 1902[a)] first published a complete scheme for single-phase electrification. The following general reasons were given for the adoption of this system:

Very high tension with relatively low current can be used for the contact system; low tension on the motors and the regulating apparatus, which vary the tension effectively, so that the speed can be adjusted from zero to maximum. The motors can be constructed so that they can be used satisfactorily both for direct- and for alternating-current.

[With the single-phase system the duration of a disturbance due to short-circuit is less than for the ordinary direct-current system,]

a) 115- p.117

With the single-phase system the duration of a disturbance due to short-circuit is less than for the ordinary direct-current system, because there are no rotating converters but only transformers in the single-phase substations, so that the secondary tension immediately can be brought up to normal height as soon as the short-circuit is cleared. The transformers have also much greater momentary overload capacity than rotary converters and their efficiency is very high over a wide range; it may be 5-10% higher than the efficiency of a rotary converter system considered from the generating stations to the traction motors.

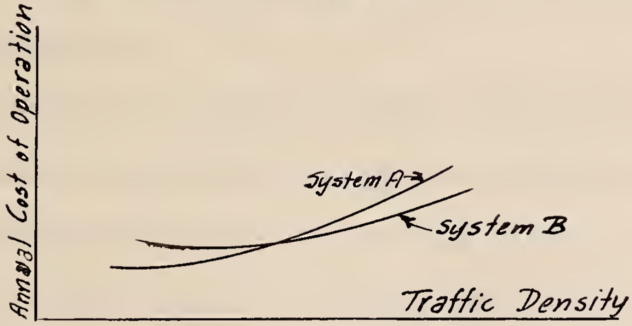
All this may be said equally well about modern developments of the direct-current system especially in regard to substations. [Therefore a special chapter shall be devoted to direct-current substation equipment.]

SELECTION of System to be Used

Hardly any technical problem has been subject to more controversy than the question of which system is the better one for electric traction. For years the railway authorities and railway engineers discussed the advantages and disadvantages of the different systems and no final conclusion has yet been arrived at. This controversy has been very harmful to the electrification of railways all over the world and has delayed quite unreasonably the adoption of a general plan for electrification. It was natural for the railway companies to be reluctant about adopting any system when they were faced with the probability of radical changes and developments in the art of electric traction and in case they did choose, the possibility of scrapping very expensive equipment in order to keep up with the time or in order to fit into another adopted standardized system.

In the meantime the discussion has lost some of its sting, since actual operation of all four systems has proved that safe, reliable and economical operation can be had by either of them, the difference in the various lines of performance being so small that only the most careful consideration of all factors may show slight advantages of one system over the other. Technically, at least, it must be concluded that the single-phase alternating-current system and the high-tension direct-current system are about equal.

Comparative estimates of economics for different railways within the same country show that for some railways the one system is the more economical one; for others the other system has the advantage. Everything depends upon local traffic conditions. For one and the same railway the total annual costs of operation in relation to the traffic density for the different systems would, in diagrammatical form,[a] show two lines close to each other and intersecting at a certain density.



Thus for a low traffic density system A should be used, but as the volume of traffic increases system B would be more economical.

This clearly brings out the impossibility of selecting one system which now and in the future would be the best for railways of very different traffic conditions.

In order to make a selection anyway, it is necessary to consider each railway system by itself and as far as possible correlate it to a general scheme of electrification; and when first a system has been selected it will practically always be necessary to adhere to it for future extensions.

[a] 123- p.8

Decisive for such extensions is the success of actual operation of the electric railway. This is not so much dependent upon the system used as the fulfilment of the following requirements: All the plants for the electrical railway and all locomotives should be adequately designed and carefully constructed; all the electrical equipment should be systematically inspected to ascertain its fitness for use, and should if necessary be repaired in suitable repair shops; finally ~~should~~ all persons engaged in the operation and inspection of the electric railway should be well trained technically in order to appreciate the peculiarities of electric service.

When these requirements are satisfied ~~have~~ the different railway companies have generally no reason to change a system which they have operated for years and in the operating of which they have gained valuable experience and to which its repair shops are adapted and its workmen are trained.

Another element of the greatest importance is the position of the manufacturing companies and their adaptation to the different systems. For example, Holland was undoubtedly influenced in the choice of the direct-current system by the fact that by adopting this system it would conform to the general practice in the adjacent countries, England, France, and Belgium and thereby secure greater competition between the contractors. Besides, in this case the Dutch industry would be able to manufacture some of the electrical equipment.

In America this influence of the manufacturers has been very decisive. Here, the General Electric Company is the strong proponent of the direct-current system and their manufacturing plants are adapted to the direct-current motor. Due to the great influence of this company, many other countries, for example Spain, have un-

[illegible]

doubtedly chosen the direct-current system for future extensions.

For the supply of alternating-current equipment ~~a~~ in American only the Westinghouse Electric and Manufacturing Company can be considered and this company has also exercised great influence in the electrification of several lines.

There are several great electrical manufacturing companies in Europe particularly in Germany, Switzerland and Sweden which have delivered many alternating-current locomotives. The industries of the other countries have not been able to develop a satisfactory single-phase motor and to this fact must, probably to some extent, be attributed the reason why in Europe none of the different systems prevails.

Finally it should be mentioned that there are several other interests outside the railways and the manufacturers which may influence the selection of system. The telegraph and telephone companies have in some countries great misgivings in regard to the single-phase system, because they fear great expenses due to the disturbances from the single-phase railway current. Furthermore, in the United States the power companies are supposed to have interest in favoring the direct-current system, because the companies prefer to use 60 cycles on their general power network, and whereas this frequency lends itself readily for conversion to direct-current it is not suitable for single-phase railway operation without conversion.

USE OF DIFFERENT SYSTEMS

As this question will later be taken up in greater details here will be given only a short summary a) of the practice in the different countries and a few important lines will be mentioned.

In general it may be said that the direct-current system prevails in the Western part of Europe. The single-phase alternating-current system previals in Central and Northern Europe and the three-phase alternating-current system prevails in Northern Italy; but there are important single-phase lines in Middle Italy and direct-current lines in South Italy.

France, England, Holland, Belgium and possibly Spain have expressed themselves in favor of the direct-current system, although in all countries there are important single-phase railways.

In Switzerland the single-phase system has been adopted for the Federal Railways although several lines have been electrified with the direct-current system.

In Germany and Austria the single-phase system is used almost exclusively and the same may be said about Norway and Sweden.

In the United States of American these are important lines using either the direct-current system or the single-phase system and there has been one three-phase installation in a tunnel through the Cascade Mountains. This line has now been changed to single-phase operation.

A line which has had great influence upon the electrification of other railways is the Chicago-Milwaukee line. With this as a pattern Mexico, Brazil and Chile adopted the direct-current system with 3000 Volts. Canada has also seen an advantage in adopting this system using only 2400 volts.

In Australia and Africa there are several railways using the direct-current system and the same is true of railways in Asia, particularly in British-Indies, Dutch-Indies and in Japan. In most of these cases it is the choice in the mother country which has to a great extent influenced the choice of system.

a) 115 - p.100

THE FOLLOWING TABULATION GIVES A SUMMARY OF THE PRACTICE IN THE DIFFERENT COUNTRIES

England	600 and 1500 V. dc.
Brazil	3000 V. dc.
France	650, 850, 1500 V. dc.
Italy	650, 4000, 5000 V. dc. 3000, 3400, 3700 V. ac.
Austria	500, 700, 750 V. dc. 1200, 2500, 5000, 15000 V. ac.
Norway	16000 V. ac.
Sweden	15000 and 16000 V. ac.
Switzerland	750, 5000, 11000, 15000 V. ac.
Australia	1500 V. dc.
Holland	1500 V. dc.; 10000 V. ac.
Japan	600, 650, 1500 V. dc.
New Zealand	1500 V. dc.
Prussia	10000 and 15000 V. ac.
Hungary	1000 V. dc.
Chile	2400 and 3000 V. dc.
Mexico	3000 V. dc.
Java	1500 V. dc.
Germany	800 V. dc.; 1500 V. ac.
U. S. A.	
New Haven	650 V. dc.; 11000 V. ac.
New York Central	650 V. dc.
Pennsylvania	600 and 675 V. dc.; 11000 V. ac.
Baltimore and Ohio	600 and 675 V. dc.
Chicago, Milwaukee & St. Paul	3000 V. dc.
Delaware, Lackawanna & Western	3000 V. dc.
Long Island	600 and 650 V. dc.; 11000 V. ac.
Michigan Central	650 V. dc.
Illinois Central	1500 V. dc.
Southern Pacific	1200 V. dc.
Canadian National	2400 V. dc.
Erie	1200 V. dc.
Boston & Maine	11000 V. ac.
Norfolk & Western	11000 V. ac.
Virginian	11000 V. ac.
Great Northern	11000 V. ac.
D. T. & I.	22000 V. ac.

ELECTRIC RAILWAYS IN SWITZERLAND

General. The electrification of railways in Switzerland was exceptionally desirable due to the country's geographical, economical and political conditions.

As is well known the country is very mountainous, so the railways encounter very steep grades, sharp curves and many tunnels, all conditions which make it desirable to have electric operation. Switzerland has no coal resources whatever, so for the operation of its industry and railways it is wholly dependent upon foreign countries. But it has a wealth of available water-power within easy reach of its railways, so electrification seemed especially desirable also from that viewpoint. Since practically all railways in Switzerland are owned and operated by the Federal Government, uniformity of service was secured so that all that had to be done was to make a decision whether to electrify or not and to make a choice of the system to be used.

For this purpose a commission was appointed about 1910. ~~and~~ This commission made a very comprehensive survey of existing railways in Europe and in the United States and published several voluminous reports[a)] on their findings, some of which are reviewed subsequently. The commission also made complete estimates on the cost of the construction and operation of typical railways in Switzerland, but as these are somewhat antiquated they are not referred to in detail.

SURVEY of Existing Railways (1915)

The commission first investigated the energy consumption of different existing railways.[b)] The evaluation of such empirical material is exceedingly difficult and great caution must be exercised in the application of such data on another railway.

There are for each particular railway, many variable factors of the greatest significance that influence the energy consumption,

a)117 b)118-p.22

such as profile of track, traffic conditions, etc. In order to find reliable, comparable figures for a certain railway it would be necessary to operate this particular railway with the different systems under similar conditions; and this is impossible in practice.

Regarding the efficiencies of the different systems one can find some mean values for the different parts of each system. For the locomotives the commission lists the following average efficiencies of the then existing types:

Direct-current	Single - Phase	Three - Phase
0.70 - 0.80	0.68 - 0.75	0.65 - 0.70

These values do not regard the possible regeneration of energy and they vary according to the use of the locomotive, whether it is for express - service, freight - service, etc.

For the complete traction system the following efficiencies were listed[a] by the commission:

	Direct-current	Single-phase	Three-phase
Locomotives	0.70-0.80	0.68-0.75	0.65-0.75
Trolley and rail	0.94-0.98	0.94-0.98	0.94-0.98
Conversion or transformation	0.70-0.90	0.90-0.95	0.80-0.90
Transmission	0.90-0.95	0.90-0.98	0.90-0.95
Total effeciency from generating station to locomotive's wheel	0.42-0.67	0.53-0.63	0.44-0.63

It is seen that the mean efficiencies for the different systems do not vary much, whereas the values for each system vary considerably according to different conditions.

However, the efficiency alone of a system does not constitute a criterion, whether a system is superior or not to another. One must consider the total annual charges in order to give any significance to a comparison. In this case the commission found that the high efficiency of the direct-current system with favorable substation operation would be more than offset by the high cost of construction and the high annual charges.

The commission also investigated the feasibility of using accumulator batteries for carrying the peaks of the system, and to

a) 118 - p. 23

that end the efficiencies, cost of construction, annual charges and cost per KWh delivered to trolly are calculated for the part of the system related to this scheme. It was found that the three-phase system is much less economical than the two other systems, mainly due to the double-pole trolley necessary for the three-phase system.

Two schemes of accumulator back-up were considered,, namely central back-up (at generating station) and substation back-up. For the direct-current system the central back-up was less economical than substation back-up; for the three-phase system the two systems were equal; for single-phase the central back-up was the best.

The results[a)] are listed below and it is evident that the single-phase system in this respect is by far the most economical.

Increase in Cost due to Accumulator Back-Up

(The figues in parenthesis refer to dense traffic; the others to medium traffic)	Direct-current 3000 volt Substation Back-up	Single-Ph. I5000 volt Central back-up	Three Ph 5000 Volt Central back-up
Every KWhr delivered to trolley corresponds to KWhr from transmission line	I.54(I.40)	I.65(I.50)	I.65(I.55)
The cost expressed in per cent	I00 (I00)	I07 (I07)	I07 (III)
The cost of convers.in per cent	I36 (64)	68 (43)	93 (50)
Comparative cost per deliv.KWhr	236 (I64)	I75 (I50)	200 (I6I)

Estimates for a Particular Railway

No definite conclusions can be made from general, theoretical considerations. Comparative estimates of real value can only be given for total cost of construction and cost of operation for a particular railway. Therefore, the then existing Gotthard Railway was chosen as the basis of comparison, which comprised the total cost and annual charges on transmission and contact system, the energy consumption and the cost of energy at the generating station. The total cost and annual charges of the remainder of the system, such as the Locomotives and Signal System, are by all systems approximately the same.

a) 118-p.76

Supply of Power. It was found that the scheme of using accumulator batteries as a back-up was uneconomical for all systems and for all traffic densities. The generating stations had to be built large enough to carry the maximum load.

Comparison of Systems All three electric traction systems considered were found to meet satisfactorily the technical requirements for electric railway service when properly designed and constructed. However, the single-phase system had the greatest technical advantages and should, therefore, be recommended.

In regard to economics, the direct-current system using 3000 volts was found far inferior to the single-phase system and a ~~still~~ higher voltage of 8000 volts was found still more uneconomical.

The three-phase system even of the highest practicable voltages was also found less economical than the single-phase system.

CONCLUSION

The commission arrived at these results when considering the Gotthard Railway. However, as the conditions on other parts of the Federal Swiss Railway system are in the main quite similar to those met at the Gotthard Railway, it is possible to generalize the results found.

As the single-phase system was found superior to the other systems both in regard to technical and to economical considerations, the commission concludes[a)] that the single - phase system using motors with series-characteristic and 15000 volt, 15 cycles, is for the conditions of the Swiss Railways the preferable system both technically and economically.

a) 118 - pp. 233-35

THE ELECTRIFICATION OF THE GERMAN RAILWAYS

General Traffic conditions in the Southern states of Germany are somewhat similar to those met with in Switzerland. For this reason and also because there is a great surplus of available water power in those states, it was quite early recognized that there were great advantages connected with the electrification of the railways. The authorities of the state railways in Bavaria and in Baden selected at an early stage of the development of electric railways the single-phase system to be generally used. a) The reasons for this choice were much more of an economic nature than they were technical and quite particularly such that were essential to good train service.

The steam railways have built up through decades of experience an admirable train service and in order that the electrical operation shall not in any way be inferior to the steam operation in regard to reliability and punctuality, it is essential that the system of apparatus introduced in the electrification should be as simple as possible and consisting of as few parts as possible. In other words any complication and intricacy of apparatus should be avoided in the design of the whole system from generating station, transmission system, contact system to locomotives.

Consideration of Systems.

This requirement makes it apparent that it would be desirable to generate in the central stations the same form of energy as the train consumes. This would eliminate the substation and thereby reject the direct-current system, which requires one form of current for transmission and another for traction.

Of the two ~~other~~ alternating current-systems, the three-phase and the single-phase systems, the former has apparently the advantage that the current can be drawn directly from the general light and power network, provided, naturally, that the voltage and frequen-

a) 119-c.1

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

cy are the same.

Supply of Energy

However, the amount of energy required for a heavy train service as found in Germany is generally so large that not only are special generators with switching equipment necessary, but separate transmission lines must also be provided.[a] Therefore, the ordinary distribution system for energy supply will in general not be able to take care of the increased demand due to railway electrification. It is also highly essential that the highest degree of reliability of service is assured which makes it desirable to generate the current in special stations, primarily built for railway supply and preferably the stations should be owned and operated by the railway company in order to have complete control of energy supply and load dispatching. For these reasons there is no necessity of fitting the railway system into existing networks.

Technical Comparison of Systems.

The three-phase system has one great advantage, namely that the three-phase motor has no commutator, which is a constant source of trouble, and one might feel tempted on account of this advantage to overlook a decided disadvantage of this system, viz. the complication of the catenary system due to the necessary double pole trolley line.

On the other hand the single-phase system has some real advantages as the following ones:- For the transmission of single-phase current only two lines are necessary as against three lines for the three-phase current and this reduces the source of troubles on single-phase systems by two thirds as compared with three-phase systems.

Furthermore, the single-phase trolley line is single pole. Thus a considerably higher tension can be handled by this than by a

a) 119-p.16

double pole trolley required for three-phase current, since the latter is limited to a comparatively low tension due to insulation difficulties at crossings and curves. It is an essential advantage of the single-phase system that it can utilize high voltages, indeed this system can work on voltages much higher than those feasible on any other system.

Substations and Transformer Stations.

The high voltage in the single-phase trolley do not only permit small cross-section of trolley, consequently small cost of copper, but they also permit the transformer stations to be placed at a considerably greater distance than it is permissible to place substations with direct-current systems.

To illustrate this, let us assume a normal cross-section of the trolley of 95 mm² and that for a single -phase system of 15000 volts one such wire is necessary, whereas for direct-current of 3000 volts, two wires are necessary; the direct-current system has then the double amount of the expensive copper.

Furthermore, we will permit in the single-phase trolley a voltage drop of 20%, whereas in the direct-current trolley a voltage drop of 30%. This is reasonable, since the voltage in the direct-current substations is well regulated, whereas for the single-phase system there should be added to the 20% trolley voltage drop also the voltage drop in the transformers and high-tension transmission lines.

An electrotechnical calculation will then give the result[a)] when the resistance, the inductivity and the voltage drop of the contact system are considered, that the trolley length, which can be fed from a feeder point, is three times as long for a single-phase system as that for a direct-current system. There should in other words be required three times as many substations on a direct-current system as transformer stations on a single-phase system.

a) 119- p.17

However, the number of actually required substations does not only depend on the voltage drop, but much more on local requirements, since the feeder-points (and substations) must be placed in the important junctions even though in the initial development all the lines running out from the junctions are not being electrified.

Therefore, it is not possible to say in general from theoretical calculations what the relation of number of substations is for the different systems; one can only predict that for particular sections. For one such calculated line the result was that number of substations and transformer stations required was

for the direct-current system 95 substations

for the single-phase system 4I transformer stations

The relation here is (2.3):I in favor of the single-phase system, but it must also be remembered that a transformer station is considerably cheaper to operate and to maintain than ~~is~~ a substation is.

Another economical advantage of the single-phase system is, that because of the high tension, a comparatively small amount of copper is required in relation to that required for the direct-current system.

Frequency of Single-phase System

The first electric railways installed in Germany used a frequency of 25 cycles after American pattern. The railways in Hamburg are still run on this frequency. However, the further development of the single-phase motor showed that still lower frequencies would enable the construction of a motor almost equal in operation for electric traction to a direct-current series motor.

On the other hand the frequency must at least be so high as to permit the use of simple transformers with high efficiency.

A frequency which compromises between these two requirements is around I5 cycles. To begin with this frequency was therefore chosen, but later a little higher frequency, namely I6 -2/3 = 50/3, was

adopted since ~~by this frequency~~, it is possible at this frequency to draw single-phase railway current from the general three-phase light and power network with a standard frequency of 50 cycles by means of a certain one-machine-frequency-transformer.

Interference with Communication Circuit

Against the single-phase system it could be said that the electro-magnetic fields of the single-phase trolley and the use of the earth as a partial return conductor would cause disturbances on telephone and telegraph circuits.

However, this disturbance can be abrogated or at least diminished to allowable proportions by different methods. In order to simplify the adopted single-phase system as far as possible the German Federal Railways do not use any additional apparatus (like choke coils, etc) in order to mitigate such disturbances. But the essential apparatus, like generators in the central stations, motors in the locomotives, are built in such a way that as far as possible current and voltage are without higher harmonics.

Urban and Interurban Railways

For the electrification of the few city and interurban railways the Federal German Railways have not adopted any definite system, as each such railway has its own peculiar traffic conditions. In Hamburg the urban and interurban lines are operated on the single-phase system. In Berlin practically all lines are operated on the direct-current system and on an extension of the electrified system it was decided to use rectifier substations, because of the economical superiority of the rectifier over the motor-generator set.

ELECTRIC RAILWAYS IN AUSTRIA a)

The first permanent single-phase railway in the world was built in Austria and opened for operation in 1904. A tension of 2200 volts and a frequency of 42½ cycles were used.

In 1910 a general plan was proposed for electrification with the single-phase system. The reasons for the selection of this system were: 1) simple contact system; 2) flexible speed regulation and 3) low first cost of installation. Furthermore, it was desirable to cooperate with the Bavarian railways, which had adopted the single-phase system.

In 1920 the question of the use of the different systems was again considered and again the decision was in favor of the single-phase system. The main argument was now the magnitude of the efficiency from the generating station to traction wheels, which efficiency was estimated for single-phase to 60-68% against 47-61% for direct-current and 45% for three-phase.

The first cost of installation was not assumed to be decisive for the choice as the differential was small.

In 1922 it was decreed that only single-phase, 15000 volts, 16-2/3 cycles should be used for main line electrification.

a/120

THE ELECTRIFICATION OF RAILWAYS IN NORWAY

General Norway was one of the countries that during the world war suffered most from the scanty coal supply and the enormous price of coal. This extradordinary condition opened anew the discussion of electrification of the Norwegian railways and a commission was appointed in Jan. 1922 to find out if the point of time had come, where a general change ~~over~~ to electrical operation of the railways was advisable and if the proposed new lines should be built from the beginning as electric~~al~~ railways. Incidentally the commission investigated whether the general conditions are present in order to purposely electrify the railways in Norway in the tempo and extent which the state finances would allow. It was necessary, therefore, first to investigate whether technically it could be done with confidence, second, whether electric drive would be economical in operation and third, consider it in the light of national economy.

Advantages of Electrification

Besides the advantages due to the independence of foreign coal supply and the saving accruing from the substitution of Norway's abundant water power resources for the imported coal, there are a number of other technical and economical advantages connected with electrical operation.

The electrical locomotives can be overloaded for a certain time. For short periods[a)] the overloading may be 100 % ,which is of great significance during start and acceleration, since this speeds up the schedule. An overload of 15-30 % is permissible up to an hour, whereby the trains can run up steep grades without a material reduction in speed. In comparison with a steam locomotive of same power an electric~~al~~ locomotive can either surmount steep grades or increase the speed or train weight and thus effect important economies. It is very important for the conditions in Norway that a new

a)115-p.8

electrical railway can be built with about 50% steeper grades than would be feasible for a steam railway.[a)] Most of the Norwegian railways run through very rugged territory and great savings can be effected by running the new railways in open line of steep grades instead of in tunnels.

The long and steep grades in Norway may give an additional advantage to electrical operation, since it permits the use of electrical regenerative braking, whereby the motors under braking run as generators and develop power which can be utilized in other places.

Consideration of different Systems[b)]:

The three-phase system when used with 50 cycles has the advantage of using simple transformer-stations in direct connection with the three-phase network used for general power supply; only when a different frequency is used is it necessary to use rotating converting machinery.

For the direct-current system conversion from the three-phase power supply can be effected by motor-generator sets, rotary converters or mercury arc rectifiers.

For the single-phase system one can either use the three-phase power supply in connection with conversion or one can advantageously have a separate single-phase primary system, particularly where long transmission lines can be avoided. In general the best policy is to develop the electrical railway in conjunction with the general power supply.

The characteristic feature of the Norwegian railways is the long isolated lines with light traffic. In order to keep down the cost of installation it is important to use as high a tension as possible whereby the number of feeding points and the amount of copper necessary would be the minimum.

Assuming that for the maximum tensions listed below the total

a) 115-p.9 b) 115-p.12

cross section area of the catenary for the three-phase and the direct current-systems is the double of that required for the single-phase system, the following spacing of the feeding points is found.[a]

SYSTEMS	TENSION	DISTANCE BETWEEN FEEDING POINTS
Direct-current	3000 volt	40-50 Km
Single-phase	16000 "	100-120 Km
Three-phase 50 cycles	8000 "	50- 60 "
Three-phase 16-2/3 cycles	8000 "	70- 85

The cost of installing one feeder point will be least for the three-phase system of 50 cycles, but no appreciable difference will be found where conversion is necessary.

The contact system is considerably cheaper for the single-phase system than for the others. The most expensive is the three-phase system due to the double pole overhead lines.

The price of the locomotives will probably be about the same for the direct-current system and the single-phase system, while the three-phase locomotives will perhaps be 10 - 15% cheaper.

Regenerative braking can be used for all three-systems; for the three-phase system this occurs automatically when a certain predetermined speed is exceeded; for the direct-current system the range of regenerative braking is from 20 to 80 Km per hour, but the train cannot be brought to a complete stop by this braking. This, however, is possible with the single-phase system.

Regarding the disturbing influence of electric traction on communication circuits the commission found that prevention of this was purely a problem of cost. Technically, the different systems were equal, in this respect perhaps even with a preference for the single-phase system over the direct-current system, because with the former system one has more perfect means of counteracting such disturbances by means of choke-coils and special transformers.

The commission concluded that technically the direct-current

a) 115-p.4

system and the single-phase systems are equally good, while the three-phase system, on account of the complicated overhead system, must be rated somewhat lower.

For the choice of system it will, therefore, be decisive how the different systems compare with one another in economics of operation.

Comparative Estimates of Costs.[a)]

The following costs are calculated for a section of II0 Km which was assumed could be supplied with single-phase from one feeding point. The traffic is assumed to be equal to the average in Norway and all other conditions similar to the average Norwegian conditions. The prices are based on the normal price level in I9I4. The tensions used are the maximum tensions assumed feasible for Norwegian conditions, viz. for direct-current 3000 volts, for single-phase I6 000 volts (I5-I7 cycles), for three-phase 8000 volts (50 cycles).

COST OF INSTALLATION	Direct-Current	Single-Phase	Three-phase
Substations	Kr.I200 000	Kr.520000	Kr.300 000
II0 Km contact line for main line	I045 000	792000	I375 000
20 " " " at stations, etc	200 000	I70000	300 000
Control & meter wires bet. feeding points	35 000		30 000
Alteration of communication lines	275 000	440000	440 000
Automatic sectionalizing	--------	--38000	------
Total Kroner	2755 000	I960000	2445 000

The figure I,960,000 Kr. for single-phase with conversion from a three-phase power network should be modified to I,640,000 Kr. for single-phase system with direct generation of single-phase current.

Cost of Operation

The cost of operation under an assumed yearly traffic volume of 950 000 gross ton-km per km main line was calculated together with an increase of 50% in volume.

a) 115- p.16

[illegible]

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[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

As a base price for three-phase energy on the primary bus of the sub-stations was taken Kr. 30.00 per KW-year for 1914. For single-phase energy directly generated the price was taken as 40 Kr. for initial traffic density and 33 Kr. for 50% increase in traffic.

Expenses for attendants, maintenance and amortization of sub-stations and effect losses in substations are included in the following prices[a] for power delivered at the contact system.

		Prices 1914	
		Present volume	50% increase
I. Direct-current system			
Price based on	K W	3 330	4 170
Price per KW-year	Kr.	73.00	65.30
2. Single-phase system			
Price based on	KW	3 330	4 170
a. Converted from three-phase			
Price per KW-year	Kr.	52.20	49.00
b. Directly from single phase			
Price per KW-year	Kr.	48.50	40.20
3. Three-phase system			
Price based on	KW	3 630	4 550
Price per KW year	Kr.	43.40	42.00

When, furthermore, the yearly expenses for power losses, maintenance and amortization of the contact system are included and the cost thus found divided by traffic volume, one will find[b] the cost of the necessary power per ton-Km at the locomotive's pantograph.

		Prices	1914
Transport volume in gross tons		950 000	1425 000
Power-cost per gross ton-Km			
Direct-current	Øre	0.329	0.237
Single-phase" converted	"	0.250	0.184
Single-phase" direct	"	0.240	0.163
Three-phase "	"	0.294	0.216

The first cost and yearly cost of the locomotives will vary so little in comparison with the above figures that they in this connection are of no importance. As will be seen the two schemes of single-phase operation are more economical both as to first cost and as to cost of operation than the other systems.

a) 115-p.17 b) 115-p.18

CONCLUSION

The commission arrives at the conclusion[a] that although the direct-current system in a few details may show certain advantages, the single-phase system is on a whole equal to this from a technical viewpoint and it is superior to the former in economical respects.

Therefore, there is at the present time no reason to deviate from the single-phase system as it has begun to be developed in Norway, and it does not seem likely that in the future, other systems, and particularly the direct-current system, should be improved to such an extent that a complete change of the present and the proposed system would have to be made.

"No consideration of a technical or economical nature except the purely financial ones should now delay the change to electrical operation of our railways. The payment for every ton of coal, which is imported for the operation of our railways, represents the payment of interest on capital which is now invested in foreign enterprises. A corresponding capital can to greater advantage for the country be placed in electrical equipment for our railways and thereby contribute to increase the activity within the boundaries of Norway."

a) 115 - p. 24

THE ELECTRIFICATION OF THE RAILWAYS IN SWEDEN

When one of the most important lines in Sweden, namely the one connecting the capital, Stockholm, with the largest mercantile city, Gothenburg, had to be electrified due to increased traffic, a commission was appointed to consider the selection of the system to be used and the supply of power.[a]

Supply of Power Sweden has already an extensive three-phase network for light and power and particularly the section throughout which the line in question passes is amply supplied. But there is also available a large amount of water - power at a convenient distance and the question was therefore, whether the railroad should be tied in with the existing three-phase network or a separate single-phase system serving the railway alone should ~~should~~ be developed in case it was decided to use the single-phase system on the line.

It was found[b] that the general three-phase distribution network for power and light should be used for the railway supply as well, by transforming the current at suitable substations. A theoretical calculation showed that the efficiency of the electric system from turbines to locomotives was about 20 per cent better with isolated single-phase railway - power generation than with transformation from a combined three - phase railway, light and power system. But this theoretical advantage of the single - phase generation is compensated to the extent of more than one half through the lower mean load factor on the single - phase turbines for railway service. The rest of the advantage is more than offset by the extra cost and inconvenience in having two separate transmission systems.

Furthermore the reliability for the railway supply is greater with the combined system and it also gives better voltage regulation because with the combined system the voltage drop is only from substation to locomotive, whereas on the isolated single - phase rail-

a/122 b/124

way system the voltage drop is from generating station to locomotive, which generally is a greater electrical distance and therefore gives greater voltage drop.

Selection of systems The commission found that single-phase alternating current and high-tension direct current were about equally good as far as technical consideration is concerned. Estimates of costs show for some railways an advantage for the direct-current system, for others the opposite holds true depending upon traffic conditions. Regarding this main line electrification Stockholm - Gothenburg, the estimates give quite a decided advantage in favor of the alternating-current system, mainly due to the fact that it was sufficient to build five substations on a stretch of about 290 miles and these substations could be fitted into the existing three-phase power network without any appreciable expenditures for the transmission system. The arrangement of substations with single-phase is mainly decided by the call for freedom of interference with adjacent communication circuits. With direct-current the arrangement of substations is almost exclusively decided by the voltage drop in the trolley section.

For the line Stockholm-Gothenburg it was found[a)] that for the different schemes the following numbers of substations and the listed cross-sections of the contact system were necessary;

	Direct-current I500 volt	Direct-current 3000 volt	Single-phase I5000 volt
Catenary	320 mm²	320 mm²	I30 mm²
Feeder	480 "	I50 "	
Rail	I00 "	I00 "	I30 "
Total	900 mm²	570 mm²	260 mm²
Number of substations	I8	I0	5

It will be noted that these cross-section areas (I00;63:30) are inversely proportional to the number of substations.

a) 123- p.31

INTERFERENCE OF Single -Phase System with Communication Wires a)

The disturbance caused by the alternating railway current on telephone- and telegraph- wires alongside the line could not be definitely avoided except by moving those wires as far away from the line as possible, at least to a distance of 600 feet. In practice this means that these wires had to be removed from the railway and run alongside the highways. However, this would mean an excessive expenditure, so the commission proposed certain other remedies as for example the laying of a telephone cable from Stockholm to Gothenburg, by which satisfactory operation on the communication systems would be insured without excessive costs, as this cable was contemplated anyway.

The commission was not able to obtain conclusive experience about interference from high-tension direct-current railways, but it was considered likely, that by using this system the cost of the alteration of communication circuits could be obtained at a somewhat lower cost.

However, this advantage of the direct-current system was not sufficient to offset the lower operating costs of the alternating current system as the following estimate shows.

Comparative Cost Estimates for the Electrification of the Railway Stockholm - Gothenburg

The subsequent prices are based on the price level at the end of 1922 (1 Krone is 100 Øre is 26 cents)

Substation Equipment.

Single -phase, 15000 volts;
4 substations @ 3 x 3000 KVA converters, three- phase, single phase
1 substation @ 4 x 3000 KVA " " " "

Direct-Current, 3000 volts;
5 Substations @ 3 x 2000 KW Synchronous motor-generator
5 Substations @ 2 x 2000 KW " "

Direct Current, 1500 volts;
16 Substations @ 1 x 2000 KW rotary converters.
2 Substations @ 2 x 2000 KW " "

In this last case there will be complete transformer and half converter reserves in all stations. Every other station is made automatically

a)/125

controlled to bring down expenses for attendants.

Number of locomotives have been assumed to be 75.

Operating expenses have been calculated under the following assumptions;-

For the maintenance of substations and amortization expenses are figured as 5% for the electrical equipment and I.5% of the first cost for the buildings. Expenses for attendants will be 85000 Kr. for the single - phase system, I75,000 Kr. for 3000 volts direct-current, and I53000 Kr. for I500 volts direct-current. The last low figure is due to the partially automatic operation of the substation by this system.

For the contact system expenses for maintenance and amortization are set at I.5% for copper and 4% for poles, etc. For control wires 3% of first cost.

Maintenance of locomotives has been estimated on the basis of statistical material from other railways to the following figures per locomotive kilometer: for single-phase 20 øre; for 3000 volts direct-current I8 øre; for I500 volts direct-current I5 øre. For amortization is used 2.5% of first cost. The rate of interest is set at 5%.

No charges for maintenance or amortization of communication circuits have been included, since the charges involve a partial renewal of the existing system.

The operating expenses do not include expenses that are independent of the system selected, such as wages for train personnel, overhead charges, etc. For the same reason the charges for current- consumption are not included, since the energy for the different systems can be assumed to be practically the same and, therefore, without interest as far as a comparison of the systems is concerned.

The attached summary of first cost and operating expenses brings out the conclusion that the single - phase system for this line is un-

loubtedly more economical than the other systems on the assumption that all substations are tied in directly with the existing three-phase network. In fact, the conditions are very favorable for the single-phase system on this line as is brought out in the report by making similar estimates for other railways, which in some cases are in favor of the single - phase system, in other cases in favor of the direct-current system.

CONCLUSION The commission summarizes the result by saying[a]: " The supply of energy for the electrification of the railways in the South and Middle Sweden should, regardless of choice of system for traction, as a rule be affected by means of conversion from the network already existing for the general distribution.

The choice between high-tension direct-current and single-phase system is usually a choice between two equal systems. In accordance with comparative cost-estimates for the Swedish railways the single-phase system should in general be at least equal to the direct-current system, and even surpass it considerable as is specifically shown for the line from Stockholm to Gothenburg.

As the interference with communication circuits in the case of the single-phase system can be satisfactorily reduced by means of different remedies, which have been given due consideration in the cost estimates, then there does not seem to be any occasion for abandoning the single-phase system, regarding which there has been obtained several years experience in Sweden, in contrast to what is the case with high-tendion direct - current."

Therefore, the commission recommended the adherence to usual practice in Sweden by using single - phase systems for electric traction.

a)123

COST ESTIMATES FOR ELECTRIFICATION OF RAILWAY STOCKHOLM - GOTHENBURG a)

Cost of Constriction:

	Single-phase	Direct-current	
	15000 volts	3000 Volts	1500 volts
Substations.			
Electrical equipment	4600 000 Kr.	5600 000 Kr.	5200 000 Kr.
Buildings	1200 000	1800 000	2200 000
Contactsystem			
Catenary structure, etc	8600 000	8100 000	8500 000
Copper	3100 000	5700 000	8400 000
Three-phase transmission lines		2800 000	4100 000
Control wire system	300 000	350 000	700 000
Change of Communication wire			
For railway	1270 000	1270 000	1270 000
For telegraph companies	6800 000	6300 000	6300 000
Locomotives	15000 000	15000 000	13870 000
Miscellaneous & Contingencies	2230 000	2680 000	2960 000
Total Kroner	43100 000	49600 000	53500 000

Annual Cost of Operation

	Single-phase 15000 volts	3000 Volts	1500 volts
Substations:			
AMORTIZATION & Maintenance			
Electrical equipment	230 000 Kr.	280 000 Kr.	260 000 Kr.
Buildings	18 000	27 000	33 000
Attendants	85 000	170 000	153 000
Contact System			
Amortization & Maintenance			
Catenary Structures	344 000	324 000	340 000
Copper	47 000	86 000	127 000
Three-phase & control wires			
Amortization & Maintenance	9 000	95 000	144 000
Locomotives			
Amortization	375 000	375 000	347 000
Maintenance 7.5 Mil. locom. kilometers	1500 000	1350 000	1125 000
Electrolysis		100 000	150 000
Interest	2152 000	2480 000	2675 000
Total Kroner	4760 000	5287 000	5354 000

a) 123 - p.32

ELECTRICAL RAILWAYS ~~IN~~ ITALY

The Italian Government nominated in 1897 a commission to consider the question of electrifying the railways and to select the best system to be used. The commission proposed to experiment with the different systems and, therefore, accumulator locomotives were introduced on some secondary lines; a section of a main line was electrified with direct-current, 650 volts and another line was electrified with 3000 volts, three-phase, 15 cycles. The single-phase system was not tested as the single-phase motor was just being developed.

The accumulator-locomotives were soon abandoned, and, therefore, a choice had to be made between the direct-current system, and the three-phase system and it was the latter which won because of the experiences gathered. Since then the Italian State Railways in Northern Italy has been electrified with this system.

It is claimed [a] that the three-phase system offers the following advantages; the voltage chosen, 3400 to 4000 volts, enables the motors to use the line current, and the usual frequency, 16-2/3 cycles is convenient to use with the general three-phase power network with 50 cycles, Besides a frequency of 16-2/3 cycles has the advantage that the locomotives run at speeds equal to the usual train speeds with normal wheel sizes and without introducing gears.

The constant train speed is very favorable for the conditions in Italy viewed from an operating standpoint. ~~and~~ Regenerative braking, which is of great importance on these mountainous lines, occurs automatically by surpassing the normal speed. The energy consumption is considered small.

The transformer stations at the first electrified lines were placed close so that an interruption of one substation did not materially influence the operation.

a) 126-p.563

At later installations this fixed reserve has been substituted by a movable one. Some transformerstations are mounted on railroad cars, and these are pushed out on the line, where a fixed station is out of function or where a large amount of energy is temporarily needed.

There are other systems in use in Italy on private railways, both single-phase and direct-current using a tension as high as 4000 volts.

A general scheme for electrification of the State railways was started in I920. In North Italy the usual three-phase system with 3000 - 4000 volts with a frequency of 45 cycles, which is used for general distribution. In South Italy the high-tension direct-current system will be used on a main line.

Finally it should be remarked that this plan for electrification seems to have been subject to considerable criticism.

A recent report[a)] written by a consulting engineer in Milan gives some interesting up to date information on the electrification of railways in Italy.

The report first brings out the natural conditions and the difficulties in building railways in Italy due to high mountains. Next it points out the dependency of Italy on fuel supplies from foreign countries, due to its lack of coal and natural oil, but the mountainous nature of the country makes it very desirable to develop hydro-electric power plants. The electric operation of the railways would also improve traffic conditions. Besides an early experiment with battery cars which ended in failure, two systems were used with success, namely the direct-current system using 650 volts and the three-phase system using 3600 volts - I6 cycles. The single-phase system was not yet on the market. The three-phase system was adopted for main trunk lines, because it was the only existing system which could use a comparatively

a)/150

high tension on the trolley and because the motors seemed simple and satisfactory, giving regenerative braking automically. The direct-current system with the low tension then available could not operate economically on main lines, so in its original form it has only been used in few cases in Italy. The deductions as to the superiority of the three-phase system were right at that time and it is only very recently that electrification by 3000 volts d.c. has been introduced in Southern Italy. However, a three-phase system using industrial frequency (45 cycles) and 10000 volts will be experimented on a line from Rome.

There are two objections to be raised against this latter scheme. First, the inductive voltage drop is much higher at 42 cycles than at 16 cycles and the three-phase requires very careful regulation. Next, the idea was to connect all power networks and railways together, but as there are three frequencies in Italy (42, 45, and 50 cycles) this is not practicable.

The current is supplied by a 60 000 volts line running on the railway property and the substations are spaced pretty close since the three-phase motor allows only a slight voltage drop (15% maximum). The operation of the double conductor line is very onerous but a great ingenuity has been displayed by the Italian engineers in working out the difficult problems. A great number of breakages occurs with the suspension insulators. The locomotives have also caused great difficulty because the characteristic of the three-phase motors is really the contrary of what is wanted for traction and the engineers had to make great efforts to compel such a motor to do its work properly. A good traction motor must have a torque increasing with the reduction of speed. With the three-phase motor the torque cannot exceed the full-speed torque. A compromise has to be made between mechanical considerations, which re-

quire large air gap in order to avoid mechanical difficulties due to wear, and electrical considerations which require as small air gap as possible in order to keep a good power-factor. It is also a very serious objection except on the mountain sections that the motor has only 2 or 4 rigid velocities and even that only by means of complicated construction. These bad features are revealed in the maintenance expense. More than 20 % of the locomotives are continually in the repair shop and a complete overhaul which is necessary every 12 or 24 months takes from 40 to 80 days.

Telephone interference is great and it has been found necessary to remove all communication circuits 200 feet from the railway. As to future developments the report maintains that the state railways are persuaded that a gradual change to high tension direct-current is necessary because the traffic has to be sped up. At least it is certain that the three-phase system will not be further extended.

The financial condition of the private railways in Italy is very precarious. The intervention of the state is extremely heavy and the regulation of the laborers from the trade unions is such that an economic operation of the railways is not possible. Electrification is the only way of reducing operating costs and the state encourages this by giving certain subventions of about $11 000 per mile which is sufficient to pay for the contact line and the substations. The rolling stock must then be financed by private capital. The state's subvention is payable in 35 years and the state keeps a close control on the accounting, levying taxes on tickets and bills of fares and receiving a certain percentage of the income. The state also collects taxes from the other railways.

The state contributes to the construction of new lines to the extent of $72,500 per mile for main lines and $19 300 per mile for tramways, the former being sufficient in most cases to cover the cost of

construction but not the rolling stock. The amount for the tramways is entirely inadequate. The state leases the construction and operation of these new lines for a period of 50 or 75 years at the end of which the lines pass over to the state which only pays the value of the rolling stock. The lease amounts to $4,900 per mile of railway and $I,300 per mile of tramway.

ELECTRIC RAILWAYS IN FRANCE

General Before the world war and the acquisition of the rich coal fields in Alsace-Lorraine and in the Saar district, the dependence of France upon foreign coal supplies was a matter of grave concern for the French economists. Before the war France consumed annually 60 million tons of coal and produced only 40 million tons. This deficit of 20 million tons at a price of 20 francs per ton corresponded to what France considered a tribute to foreign countries of 400 million francs annually.[a)] The railroads consumed seven million tons of coal and would probably consume double this amount in twenty years.

France had, therefore, a real interest in reducing this consumption by electrification and so much more as France has a very abundant source of water-power, which is little utilized by the industries.

As usual when such a far-reaching project as a national electrification of the railways is considered a commission was appointed and made the following conclusions:

Electrification has great advantages on the lines with heavy traffic and steep grades. In comparison to steam operation it means an important economy and besides it permits the maximum utilization of material. A secondary advantage of no small import is the suppression of smoke in the long tunnels and in the vicinity of the cities.

The lines of medium steepness present sometimes certain interest in regard to electrification according to the density of traffic. For lines of medium capacity running on a level, electrification are usually uneconomical and besides the service on these lines are very well met by modern steam locomotives. As to interurban lines electification is sometimes necessitated in order to increase the capacity of transportation and to suppress smoke.

a)127- p.930

Comparison of Systems.

The three-phase system used by the Italian Railways has the advantage of the simplicity and robustness of the three-phase motor; ~~and~~ the system permits the automatic regeneration of power during periods of retardation and down hill runs and the weight of the locomotives can be as low as 30 Kg per horsepower, which it is not possible to obtain with any other system. However, there are grave objections to this system; the operation of the locomotives is not flexible as the motors run at constant speed and constant tractive effort. The equipment on the three-phase lines is complicated and expensive. For these reasons the commission found it advisable to reject the three-phase system.

The single-phase system has been used for tensions from 3000 volts to 22 000 volts and frequencies from 15 cycles to 25 cycles. In fact the tension is only limited by the insulation in tunnels as the tension can be reduced by transformers on the locomotives to a voltage convenient for motors. Or the single-phase current can be converted in the locomotives to direct-current by motor-generators sets or special converters. Thus the advantages of single-phase high tension catenary can be combined with the ideal traction performance of the direct-current motor.

The contact-system is very simple and the high tensions feasible permit great spacings of substations, but it was noticed by ~~th~~ the French commission that this particular advantage was sacrificed at certain American single-phase railways in order to suppress the interference with communication circuits.

It is seen that the single-phase system is very flexible in its application for traction and it is in fact used in its various forms on different railways.

The straight single-phase system is from a technical viewpoint very satisfactory. The single-phase series motor has an

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excellent performance for traction; the characteristic of the motor is such that the tractive effort is inversely proportional to the speed and a great advantage is that taps on the secondary side of the transformers permit the regulation of speed without losses in rheostats.

The commission found, however, that notwithstanding these advantages the single-phase system had not yet attained the degree of perfection desirable from all points of view. Particularly the electric regenerative braking for this system was as yet only in the stage of experimentation and development. Some single-phase systems do not lend themselves readily to regeneration whereas others regenerate very satisfactorily at all speeds and with a high power-factor, but no definite conclusion as to the desirability of adopting any of them was arrived at.

A material disadvantage of the single-phase system was considered the complication of the system for the protection of the adjacent telephone circuits[a], which protection would considerably increase the first cost of installation, which without this consideration would be smaller than for the other systems. Besides this the commission estimated that the cost of maintenance for the single-phase system was higher than for the three-phase and the direct-current systems and the single-phase motors were less sturdy and less capable of overloading than other types of motors.

Because of the great variety of combinations for the single-phase system the commission found it possible that some day it will be developed to a high degree of perfection but at the present stage it was far from this point in actual performance.

There is then left the direct-current system using 3000 volts tension. This system is used on a line 440 miles long of the Chicago- Milwaukee and St. Paul Railway. A special study was made of this railway and the commission found that the results obtained

a)/29-p.897

on this railway were quite remarkable.a) The energy consumption on this line has been 27 watt-hours per metric ton kilometer, whereas figures from other railways vary from 39 to 74 watt-hour per ton kilometer. The system permits a considerable adjustment of speed and the use of regenerative braking almost to the actual stopping, which the three-phase system cannot effect. It was estimated that on a certain day the regeneration amounted to II.3 % of the total energy consumed by the motors.

Strong emphasis was laid on the possibility of regenerative braking since some of the main lines in France run through rugged terrain.

For the choice of the tension to be used in France a comparison was made between 2400 volts and I500 volts, which showed that expenditures in the two cases would be about equal. This is due to the fact that the closely meshed railway system justified a much smaller distance between substations than was used for the long and isolated Chicago-Milwaukee line.

By lowering the tension to I500 volts the upper limit feasible for the use of the third rail is reached. The third rail system has a special national economical interest for France, since it permits the use of French steel for the third rail instead of the imported copper for the catenary system.

The high-tension direct-current system does not necessitate an exaggerated number of substations and the almost total absence of interference with telephone and telegraph lines constitute a very material advantage of this system over the others, at least as far as the conditions in France are concerned.

CONCLUSION

The direct-current system is more expensive in first cost than the other systems, because of the substations necessary to convert the three-phase 50 cycles current for general distribution into

a) 128 - p.277

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direct current. However, it must be remembered that in order to effect an ecomomy in this respect with the single-phase system one must generate directly the single-phase current at the low frequency by means of special generators. Otherwise, if one wants to utilize the current normally produced by the central stations (three-phase 50 cycles) one must also use rotating mediums. In regard to operating expenses only careful calculations can establish a comparison between the different systems but the commission does not find any great difference between the systems; therefore, this does not materially influence the choice of system and the commission concludes in recommending the adoption of the direct-current system with 1500 volts tension, because this is considered having most advantages for electric traction on main lines in France.

ELECTRIC RAILWAYS IN ENGLAND a)

England was one of the first countries in Europe that introduced electric operation on interurban lines. The system mostly used was 600 volts direct-current from third rail but also 1200 volts was used. Later different railways were built with the single-phase system, mainly, in order to gain experience, but also because at that time it was considered the only practicable system for long lines. The experiences gained have been satisfactory and those railways will continue to use the single-phase system also for future extensions. Still later other railways were electrified with the direct-current system 1500 volts, and also this system was found satisfactory in operation.

In 1920 the English minister for transportation appointed a commission to recommend standardization of electric railways in England. The commission recommended the 1500 volts direct-current system with either overhead or third rail and the reason for this choice was probably that the third rail has always been favored in England on account of the limited profile in tunnels and under bridges, which makes it difficult to use overhead construction. Another reason may be that the British industry is not well acquainted with single-phase equipment, and probably the fear of telephone interference with single-phase has played some rôle.

The reports of the commission do not give any explicit reasons for its choice of system.

a) 130 & 131

ELECTRIC RAILWAYS IN HOLLAND a)

General The geographical conditions in Holland are greatly different from those of most other countries. The country is very flat and the lack of mountains results in lack of water power. Thus two of the main incentives for electrifying railroads, namely steep and difficult grades and abundant water power combined with absence of coal resources, are lacking. Furthermore, there was no desire of becoming independent of foreign coal supplies, since Holland would need coal anyway for its steam-power plants.

Nevertheless, it became necessary to consider the electrification of one of the most important lines in Holland, namely the one ~~at~~ from Amsterdam to Rotterdam, simply because the line could hardly handle the increasing volume of traffic by the existing steam operation. So a committee was appointed by the government and in a report by Professor J.R.F. Franco the system recommended was the direct - current system using mercury - arc rectifiers as the converting medium from the general distributing network.

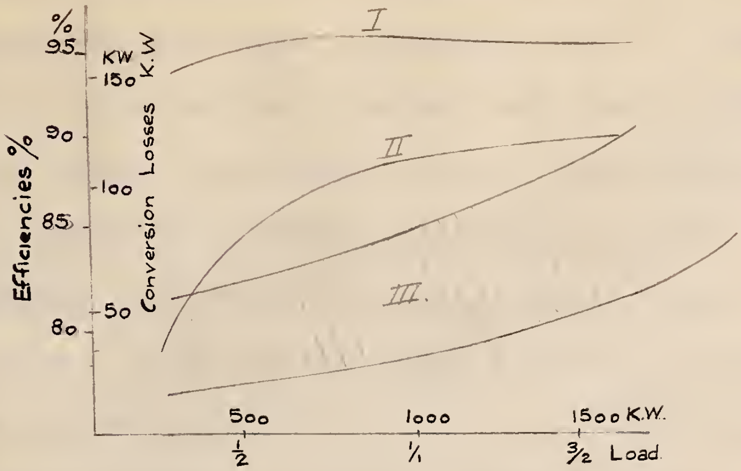
REASONS FOR ADOPTING THE DIRECT - CURRENT SYSTEM

A section of the line under consideration had been operated for a number of years on the Swiss-German-Swedish system using single - phase current. Despite this, it was decided after years of careful investigation to adopt the French system using direct - current at 1500 volts. The reason for this change in practice was the very splendid performance of some mercury - arc rectifiers tested in actual service by the Dutch railways in some of their substations, where already motor generator sets had been installed. These tests brought out decided advantages of the rectifiers both in comparison to the old alternating-current system and to the newly installed motor - generator sets. These advan-

a) 132- p.335

tages were high effciency, high degree of reliability; low maintenance cost, silent operation; small weight and much cheaper and smaller substation buildings.

For the purpose of illustrating the relative effi- ciencies of rectifiers and motor - generator sets the diagram below[a] is given;



Overall effeciencies and corresponding conversion losses.

I. Efficiency of rectifiers (I000 KW, I500 volts)

II. Efficiency of motor - generator set (I000 KW, I500 volts)

III. Shaded area shows saving resulting from the more economical operation of the rectifiers.

The efficiency curve for the rectifier is very flat; the efficiency is almost constant 95 per cent through the whole range, whereas the corresponding curve for a motor-generator set is not only much lower over the entire range, but at light loads extremely unfavorable. Thus it is seen that the conversion losses are cut by the rectifier to from I/3 to I/2 of those for the motor-generator set. This is an appreciable saving as will be seen if we assume an average load of 400 KW per rectifier and an average working day of 20 hours. At 400 KW load the saving from the diagram is found to be 54 KW; then 20x54x365 is 394,200 kilowatt hours can be saved per set per year. There are actually twenty rectifier sets

a) 132 - p.153

in the system, so the total saving is 20 x 394,000 is 7,880,000 KWh per year. Suppose the rate is 3.5 centimes per kilowatt-hour, then this represents yearly saving of about 275,000 francs.

In addition to this the maintenance cost of rectifiers is very low and as all substations are made for automatic operation, whereby a great amount of wages is saved, it will be readily appreciated why the Dutch railways chose to change their original system of alternating - current and their proposed scheme of installing motor - generator sets in the substations to their present standard of automatic rectifier stations.

CONCLUSION. The direct - current system with automatic rectifier stations was found by the Dutch Railways to give as satisfactory service and economical operation as could be reasonably asked for. It is very unlikely that Holland will regret this choice of rectifiers, which suit their purpose so admirably, since the rectifier is steadily being improved upon and important developments have occurred since the completion of this electrification. The rectifier will probably supersede the motor - generator set for railway electrification due to the ~~rectifiers'~~ many technical and economic advantages of the rectifier.

ELECTRIC RAILWAYS IN JAPAN [a)]

General The railway system of Japan is very seriously overloaded due to the rapid increase in population and to the fact that great catastrophes such as the earthquake in September 1923 caused great losses and delayed a proposed extension of the electrification of the lines having the ~~densest~~ heaviest traffic.

The electrification had been in progress since the first electric tramway was opened in Kyoto and at the present time there are over 3000 km of tramways, ~~and~~ suburban, and mountain railways

a) 133 - p. 354

using electric traction.

The reasons for electrifying the Japanese railways are threefold; first, the above mentioned great density of population and of traffic which is increaing at a rate greater than any western country; second, the severe service due to steep gradients and tunnels in the mountains of which the Japanese islands are singularly blessed; third, the scarcity of high-grade coal which makes Japan dependent on imports from foreign countries.

Japan has, however, an abundant potential source of water power. During six months of the year I4 million horse-power is available and during the other six months, six and a half million horse-power is always available. The hydro-electric plants, which can convert this vast amount of power into electric energy can very advantageously be backed up by steam power plants in which Japan's great resources of low-grade coal can be used economically. This system of supplementing hydro-electric plants with steam-power stations is much used in U.S.A. and the method of operation is to let the hydro-electric plant carry the base load or as much load as the flow in the river will allow. During non-rush hours the superfluous water can be stored behind the dam and used when the demand for power is high. By this method no water is wasted. All the time the supplementary steam-power stations are used as a stand-by for the hydro-electric stations besides carrying the fluctuations of load. By this same method the minimum amount of coal is used for the generation of electric current.

The electrification of the Japanese railways has another far-reaching economic consequence. In order to handle the increasing amount of traffic by steam operation it would have necessitated the laying of additional parallel tracks on sections of heaviest density and plans had already been made before the war for such an

increase in capacity. However, the cost was prohibitive and therefore a general scheme of electrification was taken under consideration. By this scheme a much greater traffic could be handled on existing tracks, since electric traction enables the operation of heavier trains at higher speed and frequency, whereby the capacity of the railway system can be materially increased at a reasonable cost. For suburban service the multiple-unit motor cars give a more flexible operation , since the switching at the termini is reduced to a minimum due to the fact that the motor cars do not have to be turned around. Besides, their rapid acceleration when starting permits a faster time schedule and a greater number of trains handled on the same tracks.

Current system employed.

About 75 percent of the total mileage of tracks in Japan is owned by the Japanese Government. Thus the conditions for adopting a uniform system of electrification were very favorable. As the early electrifications were made by 600 and 1200 volts direct-current, using either third rail or contact system and this system had given very satisfactory operation , it was decided about 1920 to standardize on the direct-current system, 1500 volts using contact - line but with provision for third rail.

This system was decided upon for the following reasons:

The existing three - phase networks operate at various frequencies, 25,50 or 60 cycles, and the use of an alternating - current system would necessitate the installation of frequency changers. Instead, by using automotic rectifier substations, it is possible to tie in directly with any alternating - current network used for power and light and great economies would be effected for all parties concerned.

The interference of a direct - current railway on existing telephone and telegraph wires alongside the track is much less than the influence of an alternating - current railway. So by adhering to the direct-current system already used large expenditures would be saved on the alteration of communication circuits.

Conclusion. The direct current system universally adopted in Japan is there to stay.[a] It is significant that when a country has gained satisfactory experience with one system there is a strong tendency for it to stick to it and for good reasons. First, a change-over would mean the scrapping of much material otherwise usable; second, the introduction of new types of machinery means an expensive and cumbersome renewed collection of experience with untried types of apparatus; third, when the local factories and repair shops are outfitted for a certain type of work and the workmen are trained along this line, it causes great inconvience to make any material change of practice.

a) 133 - p. 373

ELECTRIC RAILWAYS IN THE UNITED STATES

In the United States of America several important railroad terminals and tunnels have been electrified with the low-tension direct-current system using third rail. Of special importance a) are the following:

New York Central Railroad's tunnel and station in New York
Pennsylvania Railroad's tunnel and station in New York
Baltimore & Ohio Railroad's tunnel and station in Baltimore
Michigan Central Railroad's tunnel under the river to Canada and at Detroit

The reason for electrifying the tunnels is mainly to abate the smoke nuisance. The terminals have been electrified because of the same reason and also in order to increase the capacity of the terminals.

Single-Phase Railways b)

The first American single-phase railway was the Spokane and Inland Railway, which opened in 1906. Comparative estimates for this railway showed that the complete installation of the single-phase system cost only about one half of the installation of the corresponding direct-current railway.

The most important single-phase electrification in the United States is the New York, New Haven and Hartford Railway, which was put in operation in 1907-1908. Although it had been decided to electrify the terminal of the New York Central Railroad with 600 volts direct-current using third rail, the New York, New Haven and Hartford Railway decided to use 11000 volts single-phase 25 cycles, because it was considered more economical in installation and operation than the direct-current system with its many substations, and also because the railway company had had bad experiences on a local line using 500 volts direct-current.

a) 134 b) 135 & 136

It is possible to operate the same locomotives both on the single-phase line with overhead and on the direct-current line with third rail, since the single-phase series motor can be used on both systems.

The Pennsylvania Railroad uses the same scheme on their lines. The main station in New York is electrified with direct-current using third rail, but the interurban lines North of Philadelphia are electrified with the single-phase system. This latter system was chosen, because it was considered the best for the operation of heavy trains over long distances and the lines around Philadelphia were considered as forerunners for the main line to New York. Another reason for choosing the single-phase system was that it offered much greater flexibility of operation. It would be possible to use on the locomotives besides single-phase motors also three-phase motors (as used by the Norfolk and Western Railway) or direct-current motors in connection with motor-generator sets, rotary-converters or mercury rectifiers. In this way one could take advantage of all future developments.

A very comprehensive scheme of electrification of the main line from Philadelphia to New York has recently been announced and the system to be used is the single-phase system. The Pennsylvania Railroad Company carried on experiments for several years on the electrification of a difficult section over the Allegheny Mountains. Two systems were compared, one using 1500 volts direct-current with third rail, the other using 11000 volts single-phase. The latter was found cheaper and has been accepted in principle. It is planned to use locomotives with single-phase motors for passenger trains and with three-phase motors for freight trains. The reason for this is that it was assumed that the single phase motors would not stand the heavy current at the start and besides, the use of three-phase asynchronous motors for regenerative braking was of great importance in this case.

An important single-phase electrification has just been completed in the state of Washington, namely the Great Northern electrification in the Cascade Mountains.a)

The increased traffic volume in this section, particularly of heavy freight trains, necessitated radical improvements in operating conditions. An old tunnel had already been electrified in 1909 with the three-phase system, but it was decided to construct a new tunnel and to adopt the single-phase system as being best suitable for the required service. On the trolley is used 11000 volts which tension is lowered in the locomotive to operate single-phase motors, which in turn drive direct-current generators for the supply of direct-current energy to the traction motors.

Power is brought from a large power system, which scheme has the advantage over independent single-phase generation that the power produced during regenerative braking can be absorbed by this system and thus the wasting of this energy in a complicated rheostat arrangement is avoided.

a) 139- pp. 803, 808

DIRECT-CURRENT RAILWAYS

There are many interurban railways using the direct-current system. For this type of service the direct-current system is undoubtedly the better one, because motor-car operation is mostly used and because the trains in some cases have to operate on old 600 volt direct-current lines in and around the cities which brings about that the single-phase equipment would be heavier and more complicated than normally.

Furthermore, the power is generally bought from the large power companies so that conversion to direct-current was considered more economical. Therefore, since 1910 no new single-phase interurban lines have been built and a number of the old ones have been changed to direct-current.

The most important main line electrification a) using direct-current is the Chicago, Milwaukee and St.Paul Railway. Decisive for the choice of this system was the favorable experiences obtained at the Butte, Anaconda & Pacific Railway using 2400 volts direct-current and also because the power should be bought from the Montana Power Company at a frequency of 60 cycles, so that conversion was necessary anyway. Credit is given for the power obtained through regenerative braking and besides, this form of braking is very desirable from an operating viewpoint because of the long grades and the heavy trains.

It was first considered to use 2400 volts tension, but it was found that 3000 volts gave lower cost of installation and of maintenance, so this tension was used throughout and also on a subsequent extension.

The New York Central Railroad has recently announced a very important scheme of electrification of its main line to Buffalo. The direct-current system will be used.

a) 115-p.121

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THREE-PHASE RAILWAYS

The only three-phase railway in the United States was the electrification in 1909 of a long tunnel through the Cascade Mountains of the main line of the Great Northern Railway. It had become necessary to electrify this tunnel in order to eliminate the serious smoke conditions and to improve operating conditions through the tunnel. The three-phase system was used because of the induction motor's strong construction and its possibility of regenerative braking which was then not developed satisfactorily for the single-phase motor.

The complicated overhead system and the inflexibility of operation due to the constant speed characteristic of the three-phase motor caused the abandonment of this system in 1927 when a new tunnel through the Cascade range was constructed and the heavy grades of the Cascades were electrified with the single-phase system.

SINGLE-PHASE SYSTEM VERSUS DIRECT-CURRENT SYSTEM

The relative merits of the two systems have probably been more zealously discussed in America than in any other country and this discussion has undoubtedly delayed the electrification of railwyas in this country more than anything else. When one reads a statement from a proponent of the direct-current system one is led to the belief that that is the only one suitable for electri traction and vice versa.

The General Electric Company has always favored the direct-current system and some statements from this source[a)] will be referred to. "The initial expense and cost of upkeep of rolling stock equipment with single-phase commutating motors is fully double that of cars having the same seating capacity and equipped with direct-current motors. No new installations (of the simple single-phase system) have been made for the past two years, (1911-13), and several single-phase roads are being changed over to direct-current as fast as financial conditions will permit.

a) 137- p.62

"However, a more modern alternating-current system is the split-phase system which seems to meet operating requirements satisfactorily. The following table gives a comparison between the total efficiency for the distribution system and locomotives for a direct-current system and the split-phase system.

		Split-phase system	2400 volts Direct-current system
Freight Service	Distribution	70.5%	66.0%
	Locomotives	73.I%	84.3%
	Combined Efficiency	5I.5%	55.7%
Passenger Service	Distribution	70.5%	66.0%
	Locomotives	6I.9%	87.I%
	Combined Efficiency	43.6%	57.I%

"The total amount of electrical apparatus is greater and, therefore, the first cost higher and the efficiency lower with the split-phase than with the direct-current system. Furthermore, interference protection for the split-phase system may amount to $2,500 per mile or more."

Against this perhaps a little biased statement let us briefly review the advantages and disadvantages of the direct-current high-tension system:

The technical <u>advantages</u> of this system are:

I) Simple and reliable locomotives with good utilization of material, good efficiency and characteristics.

2) The locomotives can, at least for I500 volts, be built comparatively light, cheap and with low maintenance costs.

3) The I500 volts system is more suitable than the single-phase system for motor car operation, which is of importance for interurban service. The 3000 volts system, which is less suitable for such purposes, gives a natural extension of the I500 volts system for longer lines with heavier trains and less dense traffic. By such an extension the cooperation of light and heavy traffic can be insured.

4) The direct-current system causes less disturbance on communication-circuits than the single-phase system.

The technical disadvantages of the direct-current system are:

I) The comparatively low tension on the trolley line necessitates for lines with heavy traffic or of great length heavy and costly feeders and besides this it probably does not offer the same overload capacity or reserve for future traffic increases as does the single-phase system.

2) The direct-current may cause great disturbances due to electrolysis on adjacent iron constructions, water or gas pipes or cables.

GENERAL CONCLUSIONS

It is very interesting to note the reasons for the great complexity of electric railways. The difference of opinion regarding the advisability of adopting any one of the many systems in actual use arises from different geographical conditions in the various countries and also from political and local considerations.

For example one of the main reasons why France adopted the direct-current system was because of the interference of the alternating-current with their communication circuits and the great expense in changing them to prevent such interference.[a)] In Germany, on the other hand, it was not found necessary to take any special precautions against that.

These opposing conclusions are due partly to the different technics of the two countries, but mainly to the fact that in France overhead telephone and telegraph wires are used which are very susceptible to interference, whereas in Germany, the practice is to use communication cables which are well protected against interference.

A reason of a more political nature is that whereas in Germany both railway and telegraph lines are operated by the Government, in France the railways are privately owned, but the government disposes gratis of the railway land for its telephone and telegraph wires.

Thus in Germany due regard would be given by the telegraph administration to the railway administration, whereas in France the telephone and telegraph lines, if it was found necessary to move them, had to be moved by the particular state administration at the expense of the railway company and the latter would have no control over the plans and expenditure for the work.

a) 115-p.102

Thus it is seen that the considerations that enter into the question of selecting a system may be of financial and political art; regard to the domestic industry or to foreign connections; the volume and nature of traffic; the geographical nature of the country; nature of national resources, i.e. whether it is in the form of coal or water power; connection to existing railway systems or power systems, etc.

As has been pointed out previously there is generally no justification in changing over from one system to another, when first a choice has been made, because one system is about as good as the other.

Future Developments

How the development in the future will be in regard to technics and economics ~~it~~ is not possible to predict. Both the single-phase and the direct-current systems are in rapid development. Neither of them can be said to be perfect or to offer a fully satisfactory solution of the problems of electric traction, yet, with both systems many difficulties have been overcome by concentrated effort and constant improvements.

This gives the assurance that the last word has not been said in regard to the future status of the single-phase versus the direct-current system. As to the direct-current system great improvements can be expected in regard to conversion methods. The mercury-arc rectifier is being constantly improved by the efforts of the Brown Boveri Company and the General Electric Company and the latter company has undertaken the development of the kenotron, to be sure so far only for limited power output.

The automatization of the substations has been perfected to a high degree, particularly in America, and this permits a material reduction of operating expenses. But also in the field of single-phase traction can great improvements be expected. Experiments have been

carried on for several years in Germany with a three-phase to single-phase converter in one machine whereby the efficiency of such conversion will be greatly increased. The automatization of the transformer stations is also a problem to which much attention is given.

To compare the progress of the different systems with any degree of certainty is not possible at the present time and it is, therefore, safe to say that the question alternating-current versus direct-current system will still for many years be an open question.

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